Bulletin
of
The Geological Society of America

VOLUME 63 October 1952 NUMBER 10

CONTENTS

	Page
Drift dispersion in west-central New York. By Chauncey D. Holmes	993–1010
Correlation of the Cretaceous formations of the Western Interior of the United States. By William A. Cobban and John B. Reeside, Jr.	1011–1044
Method for determining the age of igneous rocks using the accessory minerals. By E. S. Larsen, Jr., N. B. Keevil, and H. C. Harrison	1045–1052
Submarine topographic echoes from explosive sound. By Bernard Luskin, Mark Landisman, G. B. Tirey, G. R. Hamilton	1053–1068
Short Notes	
Our shrinking globe—a discussion. By K. O. Emery and M. L. Natland	1069–1072
Our shrinking globe—a reply. By Kenneth K. Landes	1073–1074

Subscription $15.00 per year.

Publication Office: Mt. Royal & Guilford Aves., Baltimore 2, Md.

Communications for publication should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117 Street, New York, N. Y.

NOTICE—Four weeks notice of change of address is necessary. In accordance with the rules established by the Council, claims for non-receipt of the preceding number of the Bulletin must be sent the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter at the Post-Office at Baltimore, Md., under the Act of Congress of July 16, 1894.

Accepted for mailing at special rate of postage provided for in Section 1103 Act of October 3, 1917, authorized on July 8, 1918.

PAPERS IN PRESS FOR FORTHCOMING ISSUES

GRAVITY AND MAGNETIC INVESTIGATION OF THE STRUCTURE OF THE CORTLANDT COMPLEX, NEW YORK. By Nelson Steenland and George P. Woollard

HYPOSOMETRIC "(AREA-ALTITUDE) ANALYSIS OF EROSIONAL TOPOGRAPHY. By Arthur N. Strahler

CONTINENTAL SHELF SEDIMENTS OF SOUTHERN CALIFORNIA. By K. O. Emery

GLACIATION AND DRAINAGE CHANGES IN THE FISH LAKE PLATEAU, UTAH. By Clyde T. Hardy and Siegfried Muessig

EXAMINATION OF THE PHYSICS OF THEORIES OF OROGENESIS. By Adrian E. Scheidegger

CARIBBEAN RESEARCH PROJECT. By H. H. Hess and J. C. Maxwell

GEOLOGY OF THE LOS TEQUES-CUA REGION, VENEZUELA. By Raymond J. Smith

GEOLOGY OF THE CARACAS REGION, VENEZUELA. By Gabriel Dengo

GEOLOGY OF ST. BARTHOLOMEW, ST. MARTIN, AND ANGUILLA, LESSER ANTILLES. By Robert A. Christman

Note: Reprints of the two latest correlation charts (Jurassic, by R. W. Imlay, September Bulletin; Cretaceous of Western Interior, by Cobban and Reeside, this issue) are now available. Price 35 cents each. Other charts in stock are as follows:

Introduction, by C. O. Dunbar 10 cents
Cambrian, by B. F. Howell et al. 15 cents
Silurian, by C. K. Swartz et al. 15 cents
Devonian, by G. A. Cooper et al. 35 cents
Mississippian, by J. Marvin Weller et al. 50 cents
Pennsylvanian, by R. C. Moore et al. 30 cents
Cretaceous of Atlantic and Gulf Coastal Plain, by L. W. Stephenson et al. 25 cents
Cretaceous of Greater Antilles, Central America, and Mexico, by R. W. Imlay 35 cents
Cenozoic of Western North America, by C. E. Weaver et al. 20 cents
Cenozoic of Atlantic and Gulf Coastal Plain, by C. W. Cooke et al. 15 cents

Remittance should accompany order.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 63, PP. 993-1010, 8 FIGS. OCTOBER 1952

DRIFT DISPERSION IN WEST-CENTRAL NEW YORK

BY CHAUNCEY D. HOLMES

ABSTRACT

"Pebble counts" within a restricted grade-size range are used as an index of approximate lithologic composition of till and associated gravel. Materials eroded from outcrops within the area studied were deposited down-current in decreasing amounts, apparently depending largely on the relative rates at which those materials were reduced by crushing and abrasion. Also, their distribution was controlled strongly by topographic relief, with marked concentration along the major valleys.

The distribution pattern of Canadian (Precambrian) erratics shows no relation to an immediate source other than their probable distribution in the earlier drift. This fact supports the conclusion that the last glacier to occupy the area between the Valley Heads end moraine and the Ontario shore had its effective center of outflow within the Ontario basin.

CONTENTS

TEXT

	Page
Introduction	994
Advance summary	994
The problem	994
Acknowledgments	994
General characteristics of the region	994
The plateau valleys	996
Age of the drift	997
Previous work	997
Drift lithology and provenance	997
Grade-size reduction	997
Rock types and source regions	998
Grade-size composition of the drift	999
Index grade size	1000
Index grade size and the grade-size range	1000
Collection and preparation of samples	1001
Local variation in lithologic composition	1001
Drift Dispersion	1002
Sandstones and carbonate rocks	1002
Shales and siltstones	1005
"Crystalline" rock group	1005
Pre-Valley Heads drift	1006
Illustrative data on source-distance relationships	1006
Ontario basin as a center of glacier radiation	1006
General relationships	1006
Development of the Ontario basin	1007
Redistribution of drift by meltwater	1008
Summary and conclusion	1009
References cited	1010

ILLUSTRATIONS

Figure		Page
1.	Sketch map showing location of area studied	994
2.	Generalized contour map of west-central New York	995
3.	Sketch map showing the "through-valley" network in west-central New York	996
4.	Grade-size composition of end-moraine till near Sheds Corners, Cazenovia quadrangle	999
5.	Grade-size composition of till near Apulia, Tully quadrangle	1000
6.	Map showing per cent distribution of red-green sandstones in till, index grade size	1002
7.	Map showing per cent distribution of limestones and dolomites in till, index grade size	1003
8.	Map showing per cent distribution of "crystalline" rock types in till, index grade size	1004

TABLES

		Page
1.	Comparison in lithologic composition, index grade size, of end-moraine till and outwash gravel near Sheds Corners, Cazenovia quadrangle	1001
2.	Comparison in lithologic composition, index grade size, at four horizons in a 100-foot exposure of till, 2½ miles east of Otisco, Tully quadrangle	1001
3.	Comparisons showing influence of topographic elevation and distance of transport on lithologic composition of till in Finger Lakes region, index grade size	1007
4.	Comparison in lithologic composition of till and outwash gravel associated with end moraine near Tully, Tully quadrangle	1009

Introduction

Advance Summary

In western New York, glacier flow was largely across the strike of outcropping strata of distinctive lithology, and the coarser grade sizes of the resulting drift can be identified southward within reasonable and workable limits by lithologic determination within a selected grade size. Areal distribution of the "Medina" red-green sandstones, the carbonate rocks, and the plateau shales and siltstones shows characteristic patterns governed by degree of rock toughness, direction of glacier flow, and strong topographic control within the plateau. The "crystalline" erratics occur in relatively small quantities in the selected grade size but are thoroughly mingled with the other drift constituents, and show an anomalous distribution pattern.

More than 90 per cent of the exposed drift in the region was transported less than 50 miles, and activity of the glacier lobe apparently began from within the present Lake Ontario basin rather than from any place on the Canadian Shield. Structural location and features of the Finger Lakes sag are believed to have been significant factors in the pronounced glacial deepening of the Ontario basin, and therefore in the localizing of the mechanism of glaciation implied by the end- and ground-moraine deposits in the area studied.

The Problem

Although the glacial features of west-central New York have long been widely known, the drift as a sedimentary deposit has received somewhat less attention than its topographic expression. The present investigation of the glacial deposits was begun in 1937–1938 with detailed areal study of drift lithology in the Cazenovia and Tully quadrangles and in adjacent territory, and was continued through the Skaneateles quadrangle in 1939. In 1946, the field work was extended westward through the remainder of the Finger Lakes district and northward to Lake Ontario.

The purpose of the investigation has been to study the progressive changes in drift lithology southward from the Lake Ontario basin by means of "pebble counts" within a single grade size. The region is especially favorable for a study of glacial transportation and drift composition because all the known drift within the area was apparently carried by ice which moved

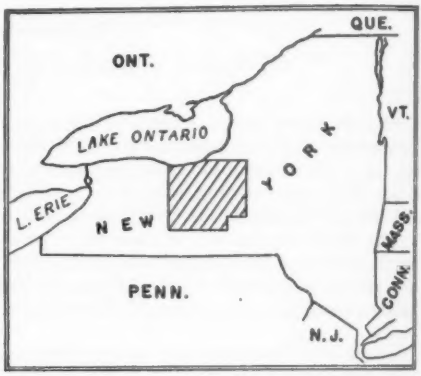


Figure 1.—Sketch Map Showing Location of Area Studied (diagonal lining)

southward across the strike of outcropping strata, each successive formation contributing to the glacier load. These materials were carried greater or lesser distances. Rock fragments of distinctive lithology can be readily identified, and their distribution as constituents of the drift can therefore be mapped.

Acknowledgments

In interpreting the detailed earlier work (1937–1938) the writer has enjoyed the benefits of critical discussion with Professor Richard Foster Flint and with fellow students at Yale University. In this way the essential plans were laid for later extension of the work. Field expenses for study in the Skaneateles quadrangle (1939) were provided by the New York State Museum. The further field work in 1946 was financed by a grant from the Penrose bequest of the Geological Society of America. Professor Paul MacClintock has given helpful criticism in the preparation of the manuscript.

General Characteristics of the Region

The area here designated as west-central New York (Fig. 1) includes about 5500 square miles, covering all or parts of 29 15-minute

quadrangles. Approximately 3000 square miles of the area lie within the Allegheny Plateau and include the well-known Finger Lakes region; the remainder is that part of the Ontario Lowland extending north from the plateau to Lake Ontario. On this lowland is the unusually fine display of drumlins and rock drumlins for which the region has long been famous. Within the plateau are the deeply eroded valleys in which earlier investigators have interpreted strong evidence both for and against large-scale glacial erosion. The rock floors of at least three of the valleys (Seneca, Cayuga, and Onondaga) are known to lie well below sea level.

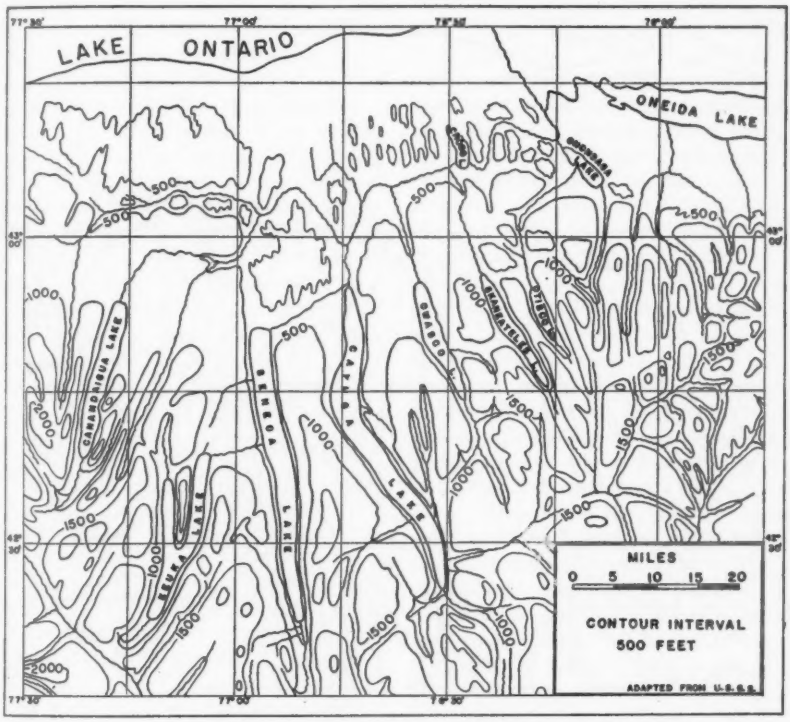


FIGURE 2.—GENERALIZED CONTOUR MAP OF WEST-CENTRAL NEW YORK

In this area the Ontario Lowland is 40–50 miles wide and rises in elevation southward from 246 feet at the Ontario shore to 600 feet or more at the base of the plateau escarpment, though in some places along the escarpment the elevation is scarcely 400 feet. In the eastern part of this area, the plateau escarpment rises abruptly at least 300 feet above the Lowland. Westward across the axis of the Finger Lakes district, the escarpment is much lower, and it is scarcely noticeable along the north end of Cayuga Lake. Cayuga and Seneca lake basins are considerably larger than the others, extending southward into the plateau a distance of about 40 miles, and together they form the axis of the group. Through the southern third of this distance, the hill summits not far distant from the lake basins exceed 2000 feet in elevation, making a local topographic relief somewhat greater than 1500 feet and a bedrock relief well in excess of 2500 feet.

At the plateau margin, the Onondaga limestone forms the principal escarpment. Minor escarpments occur southward in the plateau, developed chiefly on the more resistant sandy beds of the upper Hamilton and Portage groups. Owing to the general westward overlap of

sandy facies above the more argillaceous strata, these minor escarpments, though topographically continuous, rise westward in the stratigraphic section. At the eastern margin of the area studied (Cazenovia quadrangle), prominent scarp-forming beds occur well down in the Hamilton group.

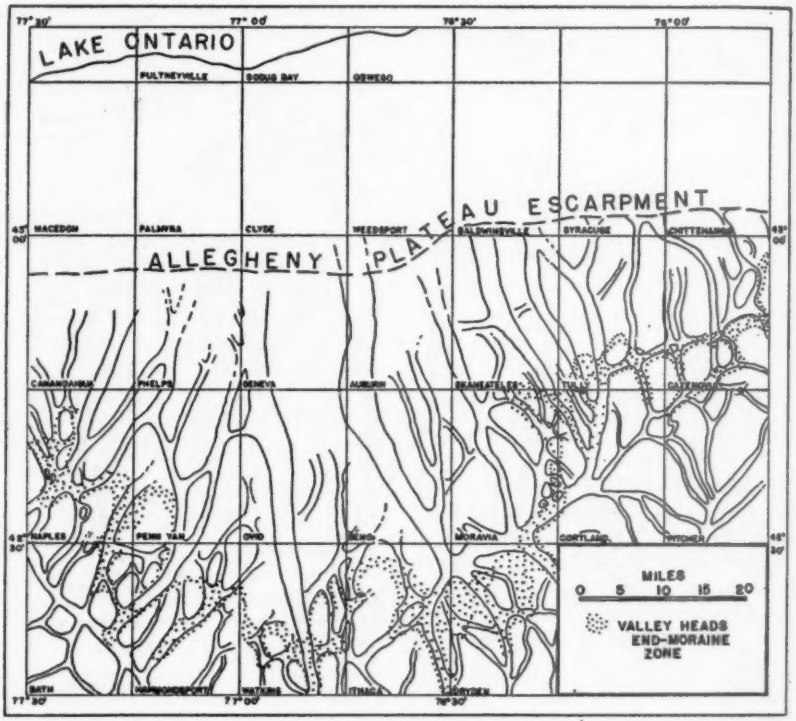


FIGURE 3.—SKETCH MAP SHOWING THE "THROUGH-VALLEY" NETWORK IN WEST-CENTRAL NEW YORK

The low elevation of the Allegheny plateau margin across the Finger Lakes district marks a prominent structural sag which tends to give a gentle southwestward dip of strata in the region as a whole. This is varied by inconspicuously low anticlinal flexures having a general east-west trend, but they have had no perceptible influence on the glacial phenomena of the region.

The Plateau Valleys

Distribution of drift in the plateau has been strongly influenced by topography, particularly by the relative depths and alignment of the major valleys. In preglacial time the minor escarpments presumably formed local, cuesta-like divides which may have been breached in places by stream capture. In many places, however, the advancing glacier, moving up an obsequent valley, crossed the divide into the resequent valley lying opposite. As these sites of crossing were the lowest along the divide, they became avenues of vigorous and concentrated glacier erosion (Monnett, 1924). As a result, the present major valleys in the plateau are deep glacial troughs. The presence of lakes in some of these troughs has diverted attention from the fact that virtually all the other valleys of appreciable size in the region are of the same general type, and all have been called "through valleys."[1] Many of the

[1] According to Tarr (1905b), the term "through valley" was improvised by W. M. Davis in discussing Tarr's paper before the meeting of the Geo-

smaller, higher-level valleys show effects of glacial erosion that illustrate incipient stages in the process of through-valley development. They form a remarkable network (Fig. 3) in which many of the valley junctions are discordant in elevation (Tarr, 1909; Holmes, 1937). These through-valleys, formed by glacial erosion, greatly facilitated the transport of drift southward to or toward the glacier margin.

Much of the glacial erosion in the plateau was evidently done by pre-Wisconsin glaciers (Holmes, 1935). However, at the height of Wisconsin glaciation, when the glacier margin extended well into Pennsylvania, the plateau of central New York must have been within the zone of active erosion. For reasons stated later, the last glacier (Valley Heads) to occupy the area is believed to have eroded significant amounts of bedrock.

Age of the Drift

A massive end moraine closes the Finger Lakes basins on the south, filling the larger through-valleys to a depth of at least half their total bedrock relief. The moraine crest forms the present drainage divide between the Susquehanna and St. Lawrence systems through most of this area. It has been called the Valley Heads moraine (Fairchild, 1932), and MacClintock and Apfel (1944) believe it represents the latter part of the Cary substage.[2] Although two minor end moraines have been recognized between the Valley Heads and the Ontario shore, the ground moraine throughout the area under consideration here is regarded as having been carried by a single glacier lobe, the two minor moraines being recessional. Evidence for this, given in later pages, is the absence of perceptible discontinuities in drift lithology though the area.

Previous Work

In their reports on the geology of central and western New York, both Vanuxem (1842) and Hall (1843) discussed the drift deposits in their respective areas of survey. Though both were somewhat skeptical of "the glacial theory," their observations merit more attention than they have since received. Both men noted the southward transportation of the drift (diluvium), that rock fragments in the drift commonly occur at elevations considerably higher than their source ledges, and that durable types such as the red and gray sandstones of the Oswego and Medina (Albion) strata, and the crystalline rocks, were spread southward through greater distances than was the rule for weaker rock types. With increasing distance of transport, the fragments became noticeably fewer and smaller. Many exceptions to these generalizations were observed and recorded, but these early reports contain no quantitative data. Very little of significance has since been published on the lithology of the central New York drift. Chamberlin cited these pioneer writers in his reconnaissance report in 1883, but the trend in glacial studies seems to have already swung toward emphasis on topographic expression and relationships and away from study of the drift as a sedimentary deposit.

Outwash gravel from the several drift sheets now recognized in south-central New York, occurring as valley-train terraces along the Susquehanna valley in Pennsylvania, have been studied by Peltier (1949). The youngest terrace is composed of Valley Heads outwash.

Near Salamanca in southwestern New York, MacClintock and Apfel (1944) recognize two drift sheets of Wisconsin age older than the Valley Heads drift on the basis of lithologic differences, but their report does not consider the west-central New York region.

Drift Lithology and Provenance

Grade-size Reduction

Two major factors have controlled the variations in drift lithology in the central New York region, as noted by the early workers: (1) the varying degrees of resistance to abrasion and crushing of the several types of rock comprising the drift; (2) the distance of transport from the source ledges. Regarding reduction in particle size during glacial transport, Udden (1914) concluded, from studies in the Midwest, that the process of crushing is of prime im-

logical Society of America at Philadelphia in 1904. The minutes of the meeting state that Davis participated in the discussion, but contain no official record of Davis' words.

[2] MacClintock (personal communication) designates the Valley Heads merely as of Cary sub-age.

portance. Field observation in the New York area on the southward (down-current) decrease in sizes and amounts of debris from different kinds of known source ledges shows that abrasion of rocks in transit also is significant. The black shales of the Marcellus and Geneseo formations, weakest of the plateau strata, afford the best illustrations because of the relatively short distances through which the effects can be seen. Till near the outcrops contains a great abundance of shale pebbles and cobbles, almost all of them deeply striated and considerably rounded. A mile or so farther away these fragments are much fewer and of much smaller average size, and no trace of them in pebble sizes or larger was observed more than 4 miles from the outcrop. The bulk of these shale materials was evidently derived by joint-block removal. By crushing and abrasion, the entire mass was reduced to fine particles within the observed distance.

At the other extreme are the Oswego and Albion ("Medina") sandstones which crop out along the northern border of the area. Fragments from these red and green quartzitic rocks are abundant in the till at the Ontario shore, and their decrease in both size and abundance southward is so gradual that they constitute a conspicuous element in the end-moraine drift as far as 80 miles from the outcrop. These rocks are toughest of the abundant drift materials—a distinction which correlates well with their slow reduction through the grade-size range with increasing distance of glacial transport.

Limestones are intermediate in degree of resistance to particle-size reduction. Near the outcrops are numerous large masses grading from angular joint blocks to subangular boulders, and an abundance of all the smaller grade sizes. In the pebble and cobble sizes, pressure-spalled surfaces are especially characteristic, with many fragments showing on one side a part of the rounded and striated surface of the larger fragment from which they were derived by crushing. Many of these older or antecedent surfaces suggest that the large stone had attained a high degree of rounding before crushing. With increasing distance from the outcrop, the larger sizes become much less common although cobbles are numerous as far as 10 miles distant and pebbles are fairly abundant in the end moraines.

Rock Types and Source Regions

The drift in west-central New York can be satisfactorily referred to four source regions. The first and probably smallest is the area of outcrop of the red and green sandstones which evidently extends northward some distance within the Ontario basin, because debris from these beds makes up a large part of the drift at and near the south shore. The second source region extends southward from the sandstone area to include the Onondaga limestone (Middle Devonian) which caps the plateau escarpment. The Onondaga and the underlying Upper Silurian limestones and dolomites supplied most of the carbonate rocks in the drift. Middle Silurian strata north of the escarpment contributed quantities of shaly material, which appear chiefly in grade sizes smaller than pebbles, and a variety of sandstones and siliceous carbonate rocks which strongly reflect the complex facies gradations in this Ontario Lowland stratigraphic section. Largely concealed beneath the drumlin drift, these rocks are probably the least known of all the New York strata.

In the eastern part of the district, drift stones from the Lowland can generally be distinguished from those derived along the escarpment. The variety of Lowland lithology increases westward, and, unless the drift stones are fossiliferous, satisfactory distinctions as to stratigraphic origin within this source province cannot be made through most of the Finger Lakes district.

The third source region is the plateau with its predominant Middle and Upper Devonian shales and siltstones. Satisfactory identification of these rocks can be made throughout the plateau.

The fourth source region is known only as that territory to the north, northeast, and possibly northwest, beyond the limits of the area under consideration, from which have come the igneous and metamorphic types and a few fossiliferous sedimentary rocks known to be older than the Oswego sandstone. Of these, the feldspathic rocks and the few schists in the drift are here designated under the term "crys-

talline." The remainder are chiefly white or tinted quartzites and an occasional marble. These rock types are present generally in small amounts, but they are nevertheless very thoroughly distributed over the entire area studied.

till beneath the margin of the glacier while the ice was in motion, with numerous small rills of subglacial meltwater escaping toward the glacier margin. Because of the meltwater action in flushing away some of the finer grade sizes,

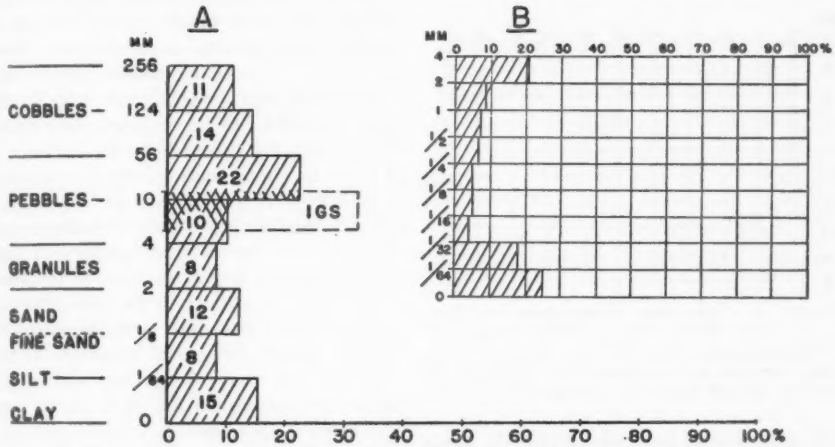


FIGURE 4.—GRADE-SIZE COMPOSITION OF END-MORAINE TILL NEAR SHEDS CORNERS, CAZENOVIA QUADRANGLE

A, entire deposit. Boulders constitute less than 1 per cent and are omitted. *B*, sample representing only smaller grade-sizes. IGS, range of the index grade size. Till is somewhat more stony than average for the region.

An unknown per cent of Valley Heads drift has been carried by one or more earlier glaciers through unknown distances in directions known only in general.

Grade-size Composition of the Drift

Mechanical analysis of the till was carried out in 1938, but only in the eastern part of the area (Cazenovia and Tully quadrangles). At that time an exceptionally favorable exposure 200 yards long and 30 feet in maximum height was available near Sheds Corners where State Highway 13 crosses a part of the Valley Heads end moraine (Fig. 4). Characteristic of the deposit is the common occurrence of small gravelly sand pockets that surround the distal ends of many of the imbedded stones, while the proximal ends (direction from which the ice approached) are inclosed in the silty clay matrix which is relatively much less permeable. Till-fabric analysis at this locality (Holmes, 1941) indicates progressive deposition of the

the deposit as a whole is somewhat more stony than the average for the region. The boulder content was calculated by counting and by measurement of boulders exposed in the outcrop. Although many were present, their total bulk was less than 1 per cent of the deposit and consequently is not shown on the histogram (Fig. 4).

A histogram of till near the inner margin of the end moraine at the south end of Butternut Valley, Tully quadrangle, is included for contrast (Fig. 5). The high per cent of material finer than $\frac{1}{64}$ mm. at this locality reflects the nearness of the outcropping thick section of Cardiff shale a few miles to the north. Also it is believed to indicate no removal of the fine silt and clay by meltwater at the time of deposition.

Although the per cent of silt and clay in the till varies considerably from place to place, the relative percentages of the several rock types of pebble size or larger is not thereby influenced to any observed degree.

Index Grade Size

The plan of restricting quantitative studies chiefly to a single grade size of till stones is a convenient method for determining the significant trends in drift dispersion, and seemed

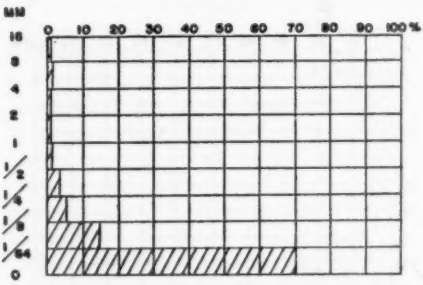


FIGURE 5.—GRADE-SIZE COMPOSITION OF TILL NEAR APULIA, TULLY QUADRANGLE

Material coarser than 16 mm. constitutes less than 1 per cent and is omitted. Per cent of fine silt and clay is much higher than average for the region.

the most feasible procedure within the limits of time and facilities available for this investigation. Accordingly the one-fourth to one-half inch size was chosen as an index to lithologic composition of the drift. This is the smallest size in which lithologic identification can be made readily, and drift samples adequately representing this grade size were found to be of only moderate bulk and weight. Actual dispersion of any one lithologic type, however, cannot be shown in terms of a single grade size because of variable distribution of that type through the several grade sizes with increasing distance from the source ledges. Moreover, quantitative regional distribution of any one rock type is partly a matter of drift thickness from place to place, and data on drift thicknesses are still too limited for quantitative calculation.

Index Grade Size and the Grade-size Range

Figure 4 gives the position of the index grade size on the general histogram of stony till. Approximately half of this particular deposit occurs in grade sizes coarser than the index. This may be taken as a tentative average for till of equivalent silt-clay content; but in till such as that in Butternut Valley (Fig. 5), nearly 95 per cent falls in grade sizes finer than the index. The position of the index grade size within the grade-size range is different for different types of rocks and appears to depend on their degree of durability and on distance of transport. Crushing and abrasion of the black shales was comparatively rapid and much of their mass was evidently reduced directly to particles finer than the index grade size. Near the outcrops, blocks of small-boulder size are common although the pebble size is by far the most prevalent but no megascopically recognizable particles remain beyond a distance of 4 miles. In strong contrast, the red and green sandstones were reduced very slowly by abrasion, and most of the products of crushing seem to have been coarser than quarter-inch size. Consequently a larger per cent of the total bulk of these sandstones in the drift either did reach the index grade size, or would have done so with greater distance of transport. At the Lake Ontario shore, Sodus Bay quadrangle, the common maximum size of fragments from this group is approximately 2 feet in diameter. Fifteen miles to the south (near Lyons), the maximum size observed was 12 inches. At a distance of 30 miles (4 miles southeast of Geneva), the observed maximum was only 5 inches.

Data on grade-size reduction now available relate only to grade sizes coarser than a quarter of an inch. A tentative summary of these data indicates that, within 15 miles southward from the outcrop, about 60 per cent of the total mass (weight) of the red-green sandstones of pebble size or larger are in grade sizes coarser than 2 inches diameter, while about 40 per cent are in the ¼-inch to-2-inch range. But within the next 15 miles this ratio is reversed, with about 60 per cent of the total in sizes less than 2 inches in diameter. Through this 30-mile distance, less than 5 per cent of the total mass is of index grade size. In and near the end-moraine zone in the Cazenovia and Tully quadrangles, about 45 miles from the outcrop, the mass of these sandstones of index grade size is slightly greater than that in the one-half to one-inch range. These data suggest that, during transportation, the per cent of the total mass of these stones of index grade size remained small and relatively constant until crushing and abrasion had reduced the supply

of coarser sizes below a critical ratio. This means that the actual rate of per cent decrease of these rocks as part of the glacier load was considerably greater than is represented by pebble counts in the index grade size. Presumably the same general principle applies also to the other lithologic types, each having its own characteristic set of ratios. This generalization rests on the assumption that the assemblage of grade sizes deposited at any one locality is representative of those that were still in transit at that locality at the time of deposition.

TABLE 1.—COMPARISON IN LITHOLOGIC COMPOSITION, INDEX GRADE-SIZE, OF END-MORAINE TILL AND OUTWASH GRAVEL NEAR SHEDS CORNERS, CAZENOVIA QUADRANGLE*

	Till 1	Till 2	Till 3	Gravel
	%	%	%	%
Red, green sandstone	6.5	6.0	5.1	6.1
Gray sandstone	1.6	1.0	1.0	1.0
Pink, white, quartzitic sandstone	2.2	2.0	1.7	1.0
Dark-, light-colored limestone	12.8	18.0	17.2	18.0
Ferruginous limestone	0.4	0.3	0.8	0.9
Chert	0.7	—	0.5	0.6
Crystalline	0.4	0.3	0.2	1.2
Shale, siltstone	75.4	72.4	73.5	71.2
	100.0	100.0	100.0	100.0

*Till samples spaced about 75 yards apart; gravel sample collected about 100 yards beyond locality of Till 3.

Collection and Preparation of Samples

Till samples of 15 to 20 pounds weight (dry) were collected generally from a single part of the outcrop, as many exposures of unweathered till are of small extent. Sieving and washing were done in a single operation with a set of screens by immersion in water. The samples yielded from 200 to 800 pebbles of the index grade size.

During preliminary study, a fairly close spacing of sample localities was observed, followed by wider spacing as experience indicated. Because of scarcity of suitable till exposures, an ideal distribution could only be approximated. In all, 135 samples of till were studied. In addition, 33 samples of outwash gravel from the eastern part of the area were studied for lithologic comparison with the local till. As most of the gravel was collected from well-exposed pits, portions of the sample were taken from different parts of the pit and the composite volume was then split to the desired quantity averaging about 500 pebbles of the index grade size.

TABLE 2.—COMPARISON IN LITHOLOGIC COMPOSITION, INDEX GRADE SIZE, AT FOUR HORIZONS IN A 100-FOOT EXPOSURE OF TILL, 2½ MILES EAST OF OTISCO, TULLY QUADRANGLE*

Samples	Near base 1	2	3	Near top 4
	%	%	%	%
Red, green sandstone	0.4	0.5	0.5	0.2
Gray sandstone	1.5	1.0	1.2	1.5
Buff, pink, white sandstone	0.4	—	0.5	0.2
Dark - colored limestone	2.0	0.8	2.5	14.0
Light - colored limestone	3.1	1.0	0.5	1.1
Ferruginous limestone	—	—	—	0.2
Chert	—	—	0.5	0.9
Crystalline	0.2	0.1	0.3	0.2
Shale, siltstone	92.4	96.6	94.0	81.7
	100.0	100.0	100.0	100.0

*Samples spaced from 10 to 30 feet apart vertically. Elevation, about 1050 feet, base of exposure.

Local Variation in Lithologic Composition

Table 1 represents till samples spaced about 75 yards apart in the end moraine near Sheds Corners. Some variation is apparent, but for purposes of this study any one of the three till samples is sufficiently representative of the drift in that vicinity.

Table 2 shows a comparison of four samples taken at intervals in the thickest single ex-

posure (100 feet) observed in the plateau area. It is located in a tributary along the west side of Onondaga Valley (Tully quadrangle). Assuming that the deposit was built up by gradual accretion, an appreciable time span is probably

Drift Dispersion

Sandstones and Carbonate Rocks

Three contrasting lithologic groups have been selected to represent drift dispersion in the

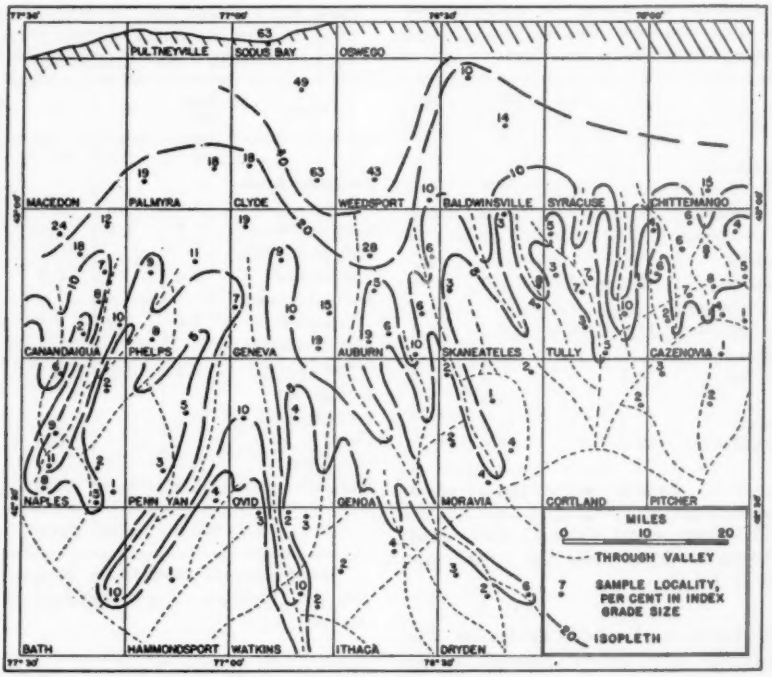


FIGURE 6.—MAP SHOWING PER CENT DISTRIBUTION OF RED-GREEN SANDSTONES IN TILL, INDEX GRADE SIZE

Generalized outcrop area of source beds in map area, above Lake Ontario level, shown by diagonal lining. Outcrop continues northward beneath the lake.

represented; yet the lithologic differences are negligible except for the amount of limestone in the highest sample, most of which is referable to the Tully formation which crops out in that vicinity. The Tully pebbles as well as the shales and siltstones are of local origin, and together make up the normal per cent of material derived within the plateau. The per cent of distantly derived materials is fairly constant throughout the entire thickness of the exposure. Topographic elevation has exercised some control in drift distribution (discussed later), but is not apparent through this particular vertical range of 100 feet.

area (Figs. 6, 7, and 8): the red-green sandstones from the extreme northern part of the region; the limestones and dolomites derived mostly at, and somewhat north of, the plateau escarpment; and the "crystallines."

Distribution patterns of the first two groups show important similarities. The maximum per cent occurs at or along the source outcrops and decreases in a regular manner toward the end moraine. Distribution is therefore definitely related to the direction of movement of the Valley Heads glacier and shows no apparent relation to transportation by any earlier glacier. No pre-Valley Heads drift has been identified

within the area, though later discovery of such drift seems probable. The isopleths show a higher rate of decrease for the carbonate rocks than for the sandstones, which is interpreted

deposition, till fabric study offers the best available grounds for interpretation.

Investigation of till fabric was carried on in the eastern part of the region in 1937 and 1938

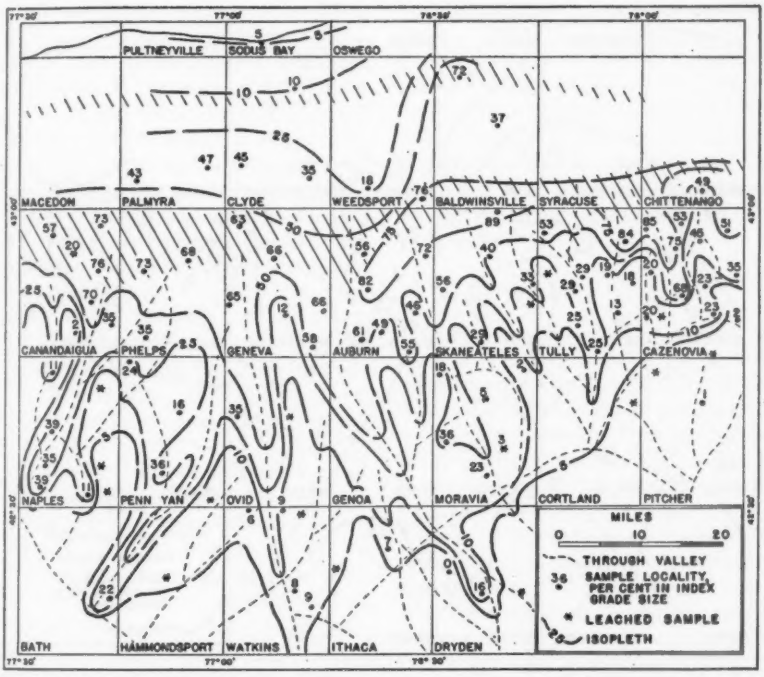


FIGURE 7.—MAP SHOWING PER CENT DISTRIBUTION OF LIMESTONES AND DOLOMITES IN TILL, INDEX GRADE SIZE

Generalized outcrop area of the more important source beds shown by diagonal lining

to reflect the relative durability of these rocks in glacial transportation.

An equally significant feature shown by the isopleths is that southward transportation was much more effective along the through-valleys than along the intervening uplands. This is quite in keeping with the interpretaton that the valleys themselves were formed by vigorously eroding basal ice currents moving by extrusion flow toward the glacier margin (Demorest, 1942; Holmes, 1937). Extrusion flow was apparently just as effective during the depositional phase as during the phase of valley deepening, and from these strong basal currents the ground moraine in the valleys was deposited. As to the mechanism of till (Holmes, 1941) and the drift there is believed to be representative of the entire area. The upper 2–6 feet of till has a relatively loose texture and probably represents the approximate depth of frost action. Beneath this zone the till is characteristically compact, and in it the stones show statistically preferred orientations. Chiefly their long axes are aligned parallel to the direction of glacier flow, though other related and equally characteristic orientations are recognized. While some investigators might interpret this as only an inherited glacier structure, deposition by gradual accretion or "plastering-on" is more in harmony with local field facts. Compaction is believed to be the result of overriding by the glacier during depo-

sition. To be deposited in this manner, a particle must be set free by melting at the base of the glacier. It has long been recognized that the temperature in the basal zone of thick glaciers is that of pressure melting, and that considerable water may exist there in temperature equilibrium with ice. Additional melting must occur from the heat of friction from shearing, sliding, and abrasion in that zone. Chamberlin (1883), in the first investigation of the Valley Heads drift, was impressed with evidence of considerable meltwater at the base of the glacier. From these considerations, the possibility of extensive deposition by progressive accretion where glacier flow was most rapid appears exceedingly strong. The thickness of drift in parts of Seneca and Onondaga valleys is well over 1000 feet, and may be equally as great in some of the others. Till on the uplands is generally no more than a few tens of feet thick and over wide areas it is less than 5 feet.

The more effective southward transport of drift along the through-valleys has left the intervening uplands with relatively low percentages of red-green sandstones and carbonate rocks. Since the upland drift is generally silty and less compact than that at lower elevations, leaching has been deeper, but where unleached exposures are available, their low per cent of carbonate rocks shows that depth of leaching has been governed also by amount of available carbonates. The red-green sandstones show comparable low percentages, and are a reliable index of original drift composition at leached exposures.

One may question whether the low per cent of northern erratic materials on the uplands may have resulted from greater admixtures of locally derived rocks. This seems very unlikely because the bedrock topography shows that glacial erosion was more effective in valley deepening than in hilltop lowering. Also, the most significant evidence of ineffective glacial

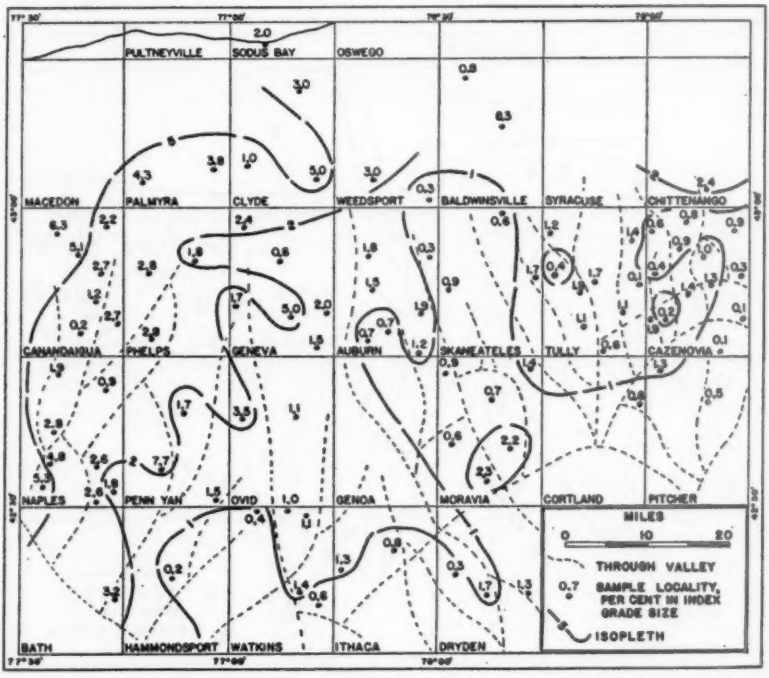


FIGURE 8.—MAP SHOWING PER CENT DISTRIBUTION OF "CRYSTALLINE" ROCK TYPES IN TILL, INDEX GRADE SIZE

erosion has been noted on the uplands (Tarr, 1905a) rather than on the lower slopes. Furthermore, there is no evidence of extensive slumping or washing of upland drift into the valleys. The smaller quantity of upland drift represents closely the original amount deposited there.

Table 3 is a summary of drift composition (dispersion) from Lake Ontario southward through Seneca valley and adjacent areas. Comparison of the till at Localities 37 and 32 shows some of the effects of relative elevation. Both localities are 43 miles from the Lake Ontario shore but one is 530 feet higher than the other and has appreciably lower percentages of red-green sandstones and carbonate rocks. Localities 40 and 34 show similar contrasts at about 65 miles from the shore. Such differences were noted early in preliminary work in the eastern part of the area where the through valleys are relatively narrow, but distribution patterns there show equally strong topographic control of glacier movement and transportation.

The influence of altitude on percentages of the northern erratics seems to be less conspicuous as the end-moraine zone is approached. A given isopleth trends definitely upward to higher elevations as it reaches the end moraine. Because of wide spacing of sample localities, and the necessarily generalized character of the maps, this feature is not adequately shown. This higher distribution in the end moraine is believed to indicate that the basal currents carrying much distantly derived drift were either thrust up over the thickened inner margin of the growing end moraine, or overrode stagnant marginal ice in the manner which Demorest (1942) has called obstructed extrusion flow.

Shales and Siltstones

Because of the relatively rapid rate at which these weak rocks were reduced to particles smaller than the index grade size, any one kind can be traced only with difficulty. An occasional red or green shale pebble from the Lowland Silurian survived transportation into the plateau, and red clayey drift derived from the Vernon shale is recognizable in the north ends of the plateau valleys, particularly in the eastern part of the area. Very little of this drift, however, was carried onto the plateau uplands.

With these exceptions, all of the shales and siltstones of pebble size or larger in the plateau drift are from the Middle and Upper Devonian rocks. Percentages in the index grade size increase southward and increase generally with increase in local altitude on account of the smaller quantities of distantly derived materials carried to the uplands. In some samples, the amount of plateau shales and siltstones exceeds 95 per cent in the index grade size, but because the upland drift is relatively thin, these percentages have little significance in terms of actual drift dispersion.

"Crystalline" Rock Group

This group consists chiefly of several gneissoid types, a few schists, and a few varieties of igneous rocks whose petrographic affinities are often difficult to determine megascopically within the index grade size. Their ultimate source was from regions well beyond the areal limits of the present study. Three significant observations may be made from their distribution (Fig. 8): (1) Most of the percentages are unusually low. About a third of the samples show less than 1 per cent, and the highest is 8.3 per cent. (2) Dispersion is virtually complete throughout the area notwithstanding the small amounts. This is the more remarkable in view of the fact that each sample represents but a small part of the outcrop sampled. (3) Quite in contrast with the other groups, the areal distribution shows almost no consistent trend or pattern as related to the general southward movement of the Valley Heads ice. However, the higher percentages are in general in the western part of the area where amounts greater than 2 per cent are common. There is a slight suggestion of southeastward decrease, but the control by local altitude seems negligible and in many cases the per cent from upland samples is higher than for near-by lowland samples. Their distribution gives no clear indication as to direction of transport, but it does show that their glacial history is more complicated than that indicated by the distribution patterns of the other groups.

The general principle of decreasing percentage with increasing distance from primary

source seems well authenticated by the distribution patterns of the sandstones and carbonate rocks. The border of the Pre-cambrian area lies at the northeastern shore of Lake Ontario, and if the Valley Heads ice had derived these "crystallines" from that area before reaching the Oswego-"Medina" outcrops, their distribution in the region south of the lake would have followed the general principle. The fact that their distribution is far otherwise justifies the conclusion that the Valleys Heads glacier derived them from some other source, believed to be the pre-Valley Heads drift.

Pre-Valley Heads Drift

The drift sheet in southern New York immediately beyond the Valley Heads end moraine has been named the Binghamton drift (MacClintock and Apfel, 1944) and was deposited by ice which flowed in a general southwesterly direction across the plateau (Tarr and Williams, 1909; writer's unpublished data). In the Pitcher and Cortland quadrangles, the Binghamton drift is relatively low in carbonate content as compared with the adjacent Valley Heads drift, though limited data now available show no decided contrast in "crystalline" content.

The Binghamton glacier evidently entered west-central New York by the most direct route from the direction of the nearest Precambrian outcrops, the Adirondacks, eastern Ontario, and Quebec. Under these conditions, glacier flow and transportation of drift were presumably more effective along the Lowland north of the Plateau escarpment than in the plateau itself, and consequently the "crystalline" materials were distributed westward more readily on the Lowland. However, low elevations of the escarpment at the Finger Lakes sag would have made southward movement from the Lowland comparatively easy, and therefore the Binghamton drift in that part of the plateau should have carried a higher per cent of Precambrian materials in pre-Valley Heads time than is now found beyond the Valley Heads end moraine.

Presumably the "crystalline" materials glacially transported from the Precambrian area were deposited down-current in decreasing quantities, though some of them in the Binghamton drift were undoubtedly carried also by one or more still earlier glaciers. At any rate, the Valley Heads ice moved in a general direction oblique to that of its immediate predecessor, crossing first the Lowland where hypothetically the "crystallines" were the most abundant, incorporating them into its load, and spreading them southward in somewhat divergent fashion with the other drift constituents. Unknown quantities of the other drift constituents must likewise have been derived from the Binghamton deposits, but the larger percentages involved and their definite relationships to source outcrops within the area completely mask the effects of earlier transport.

Illustrative Data on Source-Distance Relationships

Table 3 shows the close relationships among local bedrock type, distance of transport, and topographic elevation of depositional site. As stated earlier, the series of localities listed in the table extends southward along the Seneca valley, with two near-by localities to show lithologic contrasts due to altitude.

Silurian strata of the Ontario Lowland supplied the variety of light-colored, argillaceous, and siliceous limestones, dolomites, and dolomitic limestones which reach their maximum in the index grade size (along this traverse) in the northern part of the Geneva quadrangle. Most of the red and green shales and siltstones have also come from these strata. The persistence of this latter group southward is believed to indicate minor additions from Devonian strata on the plateau.

The type classed as gray silty sandstones, especially conspicuous in the sample from Locality 7 (Geneva quadrangle) but not recognized at adjacent localities, apparently had a restricted source not far distant and was eliminated from the index grade size within a short distance of transport. Chert appears to have been derived largely from the limestones at the plateau escarpment.

Ontario Basin as a Center of Glacier Radiation

General Relationships

Regardless of the extent to which the Valley Heads drift may have been derived from an

earlier drift sheet, more than 95 per cent of the drift studied can be referred confidently to source ledges south of the axis of the Ontario basin. Moreover, distribution of this drift shows that it was eroded chiefly by ice moving out of the basin. This erosion in Valley Heads time was sufficient to mask any earlier distribution pattern referable to the source ledges. The "crystallines," however, show no down-current decrease in percentage, indicating that glacial activity at that time was not adding to the drift any materials from the Precambrian outcrops. The whole mechanism of ice accumulation, glacial erosion, transportation, and deposition in Valley Heads time was centered on Paleozoic terrane—that is, its northern limit was within the Ontario basin. Potentially mobile ice was probably continuous to the northeast and possibly north, but was prevented from moving into the area because of the superior amounts of snowfall above the basin.

The deepest part of the Ontario basin is almost directly opposite (north of) the Finger Lakes structural sag, and its elevation is about 750 feet lower than the present shoreline.

TABLE 3.—COMPARISONS SHOWING INFLUENCE OF TOPOGRAPHIC ELEVATION AND DISTANCE OF TRANSPORT ON LITHOLOGIC COMPOSITION OF TILL IN FINGER LAKES REGION, INDEX GRADE SIZE

Locality (field number) Miles from Ontario shore Elevation, feet Quadrangle	4 0 250 Sodus Bay	52 13 425 Cylde	6 23 500 Geneva	7 33 580 Geneva	37 43 700 Ovid	32 43 1230 Penn Yan	39 57 850 Watkins	40 68 1380 Watkins	34 65 970 Bath
	%	%	%	%	%	%	%	%	%
Sandstone: red, green	84.5	18.8	9.1	17.0	8.3	5.3	3.1	2.3	10.4
Sandstone: tinted, black, white	3.5	7.1	4.0	6.3	4.0	2.0	2.3	1.7	9.9
Sandstone: gray silty	—	—	—	26.5	—	—	—	—	—
Limestone: dark	5.5	37.6	8.3	8.0	18.4	6.9	5.1	6.8	13.4
Limestone - dolomite: light, argillaceous, siliceous	—	7.1	58.0	4.0	17.8	8.7	0.7	2.2	8.3
Limestone: ferruginous	—	0.5	1.8	—	—	0.4	—	—	0.3
Shale-siltstone: red, green, var.	4.5	26.9	17.6	—	6.6	2.8	2.6	4.5	5.9
Shale-siltstone: gray, black	—	—	—	28.5	37.8	71.0	84.7	81.9	47.3
Chert	—	—	0.3	3.0	4.0	1.2	1.1	—	1.3
Quartzite	—	1.0	—	1.7	—	—	—	—	—
Crystalline	2.0	1.0	0.6	5.0	3.5	1.7	0.4	0.6	3.2
Marble	—	—	0.3	—	—	—	—	—	—
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Within the area of this study, both erosional and depositional features have a radial alignment with respect to this great locus of excavation. Depositional features are the drumlins on the bordering Lowland. In the eastern part, their long axes trend southeasterly; in the central part, southerly; and in the western part, southwesterly. This radial pattern of drumlin orientation continues into Ontario to the west and north of the lake (Putnam and Chapman, 1943; Chapman and Putnam, 1951). Erosional features include the rock drumlins (chiefly in the eastern part) and the Finger Lakes basins, as well as most of the other major through-valleys in this portion of the plateau. Some possible explanation for the deep localized erosion in the eastern part of the Ontario basin seems necessary.

Development of the Ontario Basin

Earlier explanation of deepest erosion near the eastern end of the Ontario basin has cited the probable tendency of the glacier to scour deeply as it moved southwestward from the Precambrian rocks of the Frontenac Arch onto

the weaker Paleozoic strata, the ice probably having been deflected westward by the Adirondacks (Miller, 1924). On this theory, appreciable amounts of "crystalline" material should have been brought through the basin and spread southward in the drift the same as the other drift constituents. This may have occurred as the glacier was growing or expanding southward and southwestward, but as already shown, this was not the case during Valley Heads time. This hypothesis is therefore not a complete explanation.

The common interpretation that the present Ontario basin developed from a preglacial stream-cut valley seems justified. Assuming further that glaciation began by progressive southwestward extension of snow-fields from the Labrador highlands (Flint, 1943; 1947), ice eventually filled the Ontarian valley and banked up against the north edge of the plateau, except along the Finger Lakes axis where the escarpment is inconspicuous. The lack of a barrier here permitted easy southward flow of ice through a distance of several tens of miles. Presumably this distance was significant in terms of relative ablation rates, and the higher rate of melting around the southern periphery of the Finger Lakes district maintained a surface gradient on the glacier sufficient to cause a continuing flow of ice from the Ontario valley. Extrusion flow along the base of the glacier (Demorest, 1942) would have been effective southward from the Ontario valley axis, that being presumably the zone of greatest ice thickness and hence the place of easiest movement of the basal ice. Strong erosion therefore probably began along that part of the Ontario valley nearest the Finger Lakes sag at least as soon as it did westward along the old valley. This easy southward flow into the Finger Lakes basin is therefore believed eventually to have controlled and localized the deepest excavation in the Ontario basin[3]. The great depths of bedrock erosion in the Finger Lakes valleys is considered a consequence of this concentrated mechanism of glacier accumulation and basal outflow. Each succeeding glaciation probably contributed to the deepening process. The progress of erosion permitted increased depth of ice, which in turn accelerated the velocity of extrusion flow and the rate of basin deepening. Snowfall, aided by wind drifting, could have maintained the glacier surface by filling in any depressions due to basal outflow.

The possibility that the other Great Lakes basins owe much of their depth to similar circumstances must be seriously considered. Dreimanis (1951), investigating Pleistocene stratigraphy in southwestern Ontario, concluded that "the direction of ice flow indicates the existence of a local ice center in the area now occupied by Lake Erie during a part of the Tazewell substage." The mode of origin of one of the Great Lakes basins may well be the key to an understanding of all the others, but studies of drift provenance and transport history should be made for the deposits related to each basin.

[3] A significant related fact is that the area of most profuse drumlin development lies directly north of the Finger Lakes sag, and includes the Palmyra, Clyde, and Weedsport quadrangles. Because additional factors are involved in the problem of drumlin development, no discussion of this aspect is attempted at this time.

Redistribution of Drift by Meltwater

Although the present study is concerned primarily with glacial transportation as recorded by the unassorted drift, preliminary investigation included a study of the associated gravel deposits in the eastern part of the area where 33 localities were sampled and the lithologic composition determined within the index grade size. At 30 of these localities, the lithologic composition of the gravel is almost identical with that of the till in the same vicinity (Table 1). Most of the gravel deposits in this category are of the isolated-kame, kame-terrace, or delta-kame type, and are widely distributed throughout the area (Holmes, 1947). Percentages of the weakest rock types (shales) are apparently reduced slightly by the meltwater transportation, but distances of transportation were probably less than a mile for most deposits.

The three exceptions to the general rule are significant however. A kame terrace along the east side of Keeney valley, Cazenovia quadrangle, was expected to be comparable in lithologic composition to the valley (low-ele-

TABLE 4.—COMPARISON IN LITHOLOGIC COMPOSITION OF TILL AND OUTWASH GRAVEL ASSOCIATED WITH END MORAINE NEAR TULLY, TULLY QUADRANGLE*

Sample	1	2	3
	%	%	%
Red, green sandstone	11.4	2.6	3.8
Gray sandstone	2.9	0.2	1.5
Buff, quartzitic sandstone	2.4	3.0	3.2
Dark-colored limestone	32.4	13.5	16.6
Light-colored limestone	16.3	4.6	8.0
Argillaceous limestone	—	7.0	—
Ferruginous limestone	4.1	0.3	0.6
Oölitic limestone	—	0.3	—
Chert	0.5	0.8	0.9
Crystalline	3.6	1.1	0.6
Shale, siltstone	26.4	66.6	64.8
	100.0	100.0	100.0

Sample 1. Gravel from pit on north slope of end moraine, 1.2 miles north–northwest of Tully Center.

2. Till from road cut at crest of end moraine, ¼ mile northwest of Tully Center.

3. Till from south end of small drumlin one mile south of Tully. For comparison with Sample 2.

* Composition of the till is characteristic for that distance (about 20 miles) south of the plateau escarpment, but that of the gravel is more nearly typical of till on the plateau near the escarpment.

vation) till in that vicinity, but its lithologic content corresponds to that of the upland till which is relatively poor in limestones and the red-green sandstones. This portion of the terrace therefore consists of material carried by upland drainage down against the stagnant valley ice, rather than from the valley ice itself, during deglaciation. Whitnall (*In* Twenhofel, 1932) has reported similar instances.

The other two exceptions show percentages of limestones and red-green sandstones notably higher than in near-by till. One deposit is on the proximal slope of the prominent end moraine about 2 miles west of Tully; the other is a mid-valley ice-contact deposit a mile east of Fabius, Cazenovia quadrangle. In each case the stones show considerable rounding, and the lithologic composition of each deposit is fairly typical of the drift near the plateau border about 15 miles farther north (Table 4). Presumably superglacial streams carried much of the material in these deposits from ablation debris near the plateau escarpment. This would indicate a stagnant and down-wasting ice border at least 20 miles wide at that time.

SUMMARY AND CONCLUSION

Most of the drift in west-central New York was carried by the Valley Heads glacier lobe (Ontario glacier) not more than 50 miles from its places of derivation. Down current from the source ledges, the till varies systematically in lithologic composition, but the ratio between distance of transport and rate of grade-size reduction was different for each lithologic type. While some of these results have been known in a general and qualitative fashion, the data here presented give quantitative values on the basis of an index grade size. Without quantitative data, the fact that distribution of the crystalline erratics in the areas has a markedly different pattern from those of the other drift constituents has heretofore remained unsuspected. The Valley Heads (Ontarian) glacier evidently formed and spread radially from the deepest part of the Ontario basin, and its deposits contain no record of glacial transportation from the Precambrian area during Valley Heads time.

The fact that the deepest part of the Ontario basin lies directly north of the Finger Lakes depression where the escarpment is all but absent is believed to indicate a genetic relationship to glacial deepening of the Ontario basin. Favorable ablation conditions around the south end of the Finger Lakes depression could conceivably have maintained a surface gradient on the glacier sufficient to sustain a continuing extrusion flow southward from the axis of the preglacial Ontario valley. The erosional vigor of this ice movement is believed to have resulted in great deepening of the Ontario basin and of the Finger Lakes valleys as well.

Notwithstanding the voluminous literature on the glacial geology of this area and other areas similarly situated, much remains to be done by way of investigating the lithology of the drift and attempting closer correlation with the provenance of its various constituents. Acquaintance with the lithologic composition of the drift should provide important clues to the regional stratigraphy in areas where the bedrock is largely concealed. While the present study has outlined the general principles of drift dispersion in the region, the writer believes that more detailed studies would be profitable. In the plateau where drift lithology varies with topographic elevation, important information should be obtained on the relation between the drift and the soil developed on it. Concomitant studies of local gravel deposits would afford a better interpretation of their origin and economic value. In turn, knowledge of their glacial history would lead to a better understanding of the conditions attending deglaciation in the region.

References Cited

Chamberlin, T. C. (1883) *Preliminary paper on the terminal moraine of the second glacial epoch*, U. S. Geol. Survey, 3rd Ann. Rept., p. 291–402.

Chapman, L. J., and Putnam, D. F. (1951) *The physiography of southern Ontario*, Univ. Toronto Press, Toronto, 284 pages + maps.

Demorest, Max (1942) *Glacier thinning during deglaciation, Part I: Glacier regimens and ice movement within glaciers*, Am. Jour. Sci., vol. 240, p. 29–66.

Dreimanis, Aleskis (1951) *Studies of Pleistocene stratigraphy along Lake Erie in southwestern Ontario*, (abstract), Geol. Soc. Am., Bull., vol. 62, p. 1432–1433.

Fairchild, H. L. (1932) *New York moraines*, Geol. Soc. Am., Bull., vol. 43, p. 627–662.

Flint, R. F. (1943) *Growth of the North American ice sheet during the Wisconsin age*, Geol. Soc. Am., Bull., vol. 54, p. 325–362.

—— (1947) *Glacial geology and the Pleistocene epoch*, Wiley, New York, 589 pages.

Hall, James (1843) *Natural history of New York: Geology of the Fourth District*, van Benthuysen, Albany, 683 pages.

Holmes, C. D. (1935) *Glacial and interglacial development of Chittenango Falls State Park in central New York*, Am. Jour. Sci., vol. 29. p. 41–47.

—— (1937) *Glacial erosion in a dissected plateau*, Am. Jour. Sci., vol. 33, p. 217–232.

—— (1941) *Till fabric*, Geol. Soc. Am., Bull., vol. 52, p. 1299–1354.

—— (1947) *Kames*, Am. Jour. Sci., vol. 245, p. 240–249.

MacClintock, P., and Apfel, E. T. (1944) *Correlation of the drifts of the Salamanca re-entrant, New York*, Geol. Soc. Am., Bull., vol. 55, p. 1143–1164.

Miller, W. J. (1924) *The geological history of New York State*, N. Y. State Mus., Bull. 255, 146 pages.

Monnett, V. E. (1924) *The Finger Lakes of central New York*, Am. Jour. Sci., vol. 8, p. 33–53.

Peltier, L. C. (1949) *Pleistocene terraces of the Susquehanna River, Pennsylvania*, Penna. Topog. and Geol. Survey, Bull. G-23, 158 pages.

Putnam, D. F. and Chapman, L. J. (1943) *The drumlins of southern Ontario*, Royal Soc. Canada Tr., vol. 37, Sec. 4, p. 75–78.

Tarr, R. S. (1905a) *Some instances of moderate glacial erosion*, Jour. Geol., vol. 13, p. 160–173.

—— (1905b) *Drainage features of central New York*, Geol. Soc. Am., Bull., vol. 16, p. 229–242.

—— (and Williams, H. S.) (1909) *Watkins Glen-Catatonk district, New York*, U. S. Geol. Survey, Geol. Atlas, Folio 169, 33 pages, maps.

Twenhofel and others. (1932) *Report of Committee on Sedimentation 1930–1932*, Nat. Res. Council, Bull. 89, 229 pages, p. 198.

Udden, J. A. (1914) *Composition of clastic sediments*, Geol. Soc. Am., Bull., vol. 25, p. 655–744.

Vanuxem, L. (1842) *Natural history of New York: Geology of the Third District*, van Benthuysen, Albany, 306 pages.

University of Missouri, Columbia, Mo.

Manuscript Received by the Secretary of the Society, January 7, 1952.

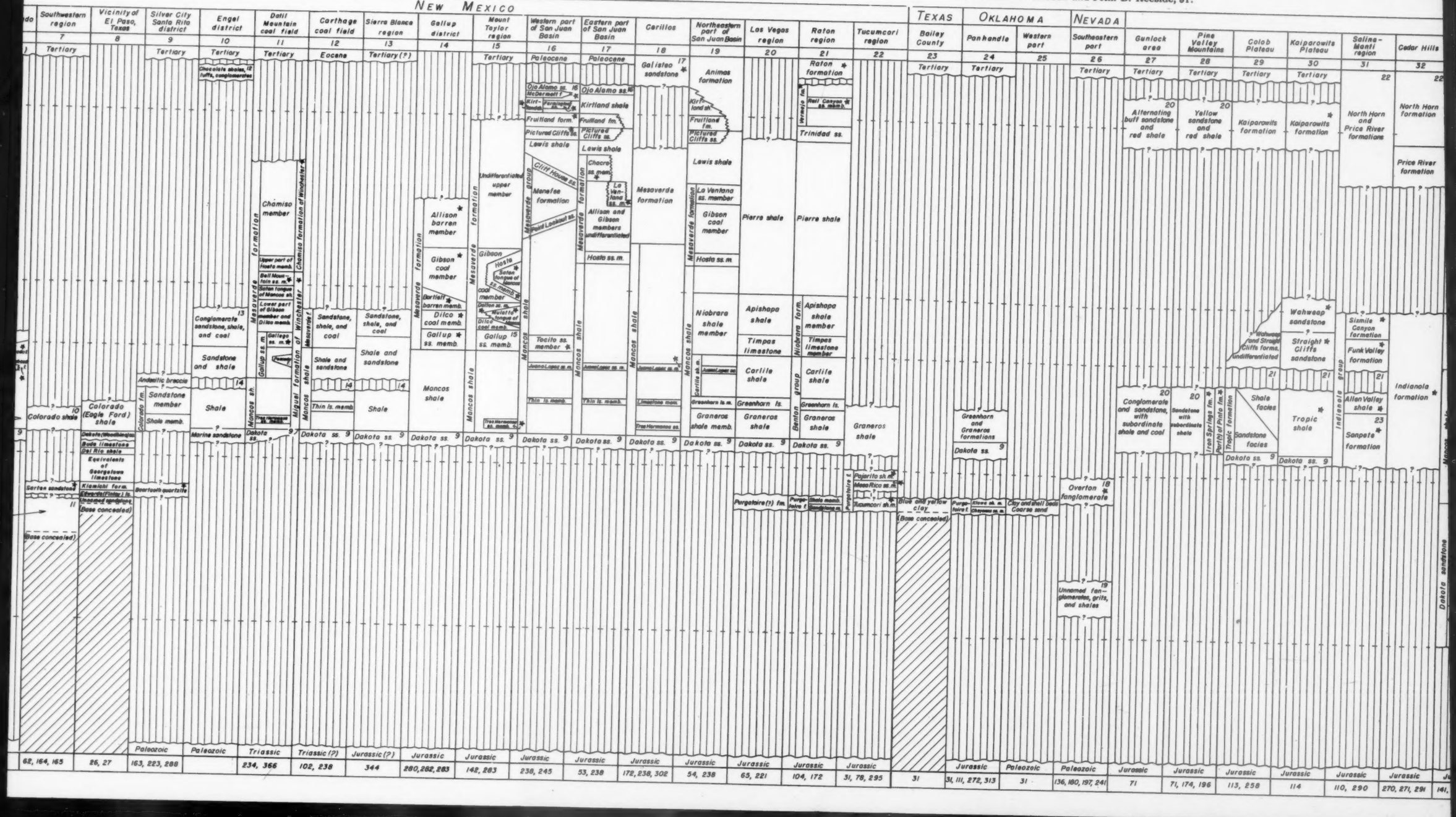
STANDARD CLASSIFICATION

Larger Invertebrate Fossils

ARIZONA — NEW

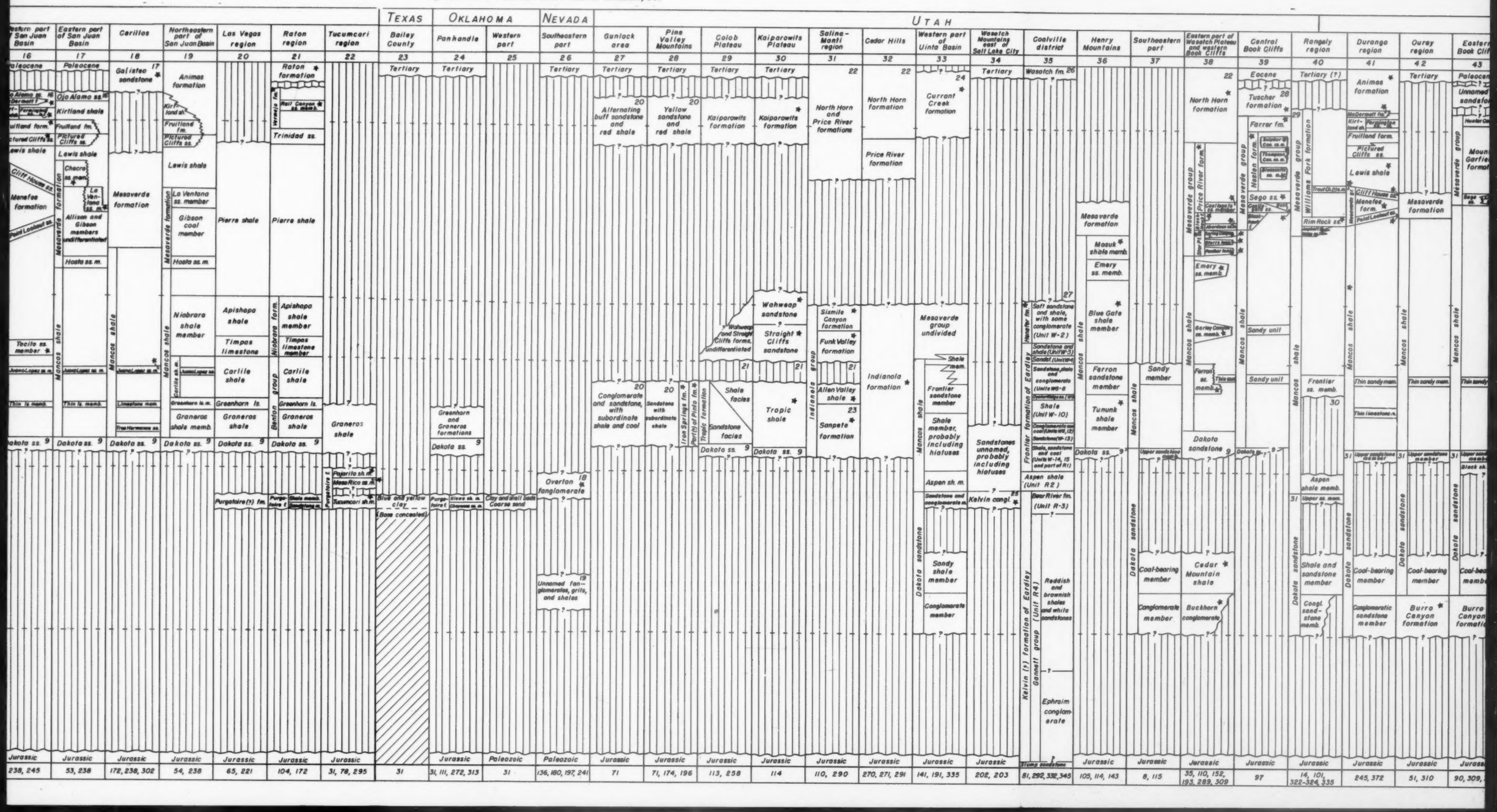
Chart 10b.- CORRELATION OF THE CRETACEOUS FORMATIONS OF THE WESTERN INTERIOR OF

By William A. Cobban and John B. Reeside, Jr.



10b.- CORRELATION OF THE CRETACEOUS FORMATIONS OF THE WESTERN INTERIOR OF THE UNITED STATES

By William A. Cobban and John B. Reeside, Jr.



STATES

Prepared under the auspices of the Committee on Stratigraphy of the National Research Council, Carl O. Dunbar, *Chairman*

COLORADO

KANSAS

Coalville district	Henry Mountains	Southeastern part	Eastern part of Wasatch Plateau and western Book Cliffs	Central Book Cliffs	Rangely region	Durango region	Ouray region	Eastern Book Cliffs	Northwestern part of Gunnison Co.	Meeker region	Vermilion Creek	Craig region	Pueblo–Welsenburg region	Colorado Springs region	Park and Summit Counties	North and Middle Parks	Foothills of northern part of Front Range	Morgan County	Yuma County	Prowers County, Colorado, and Hamilton County, Kansas	Morton County	Wallace County	Kiowa County	Ellis and Russell Counties	Decatur County	Saline County
35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61
Paleocene	Paleocene	Paleocene	Paleocene	Eocene	Tertiary (?)	Eocene (?)	Tertiary	Paleocene	Eocene (?)	Eocene (?)	(Fault contact)	Paleocene	Raton form.	Dawson arkose	"Shoshone" fm.	Coal-mont fm. / Middle Park fm.	Denver form.	Oligocene	Pliocene	Pliocene	Pleistocene	Pliocene	Tertiary	Pliocene	Pliocene	Pliocene
Coalville fm. 26	North Horn formation	North Horn formation	North Horn formation	Tuscher formation 28	Wasatch formation 29	Animas formation	Mesaverde formation	Unnamed sandstone 28	Ohio Creek conglomerate	Mesaverde group	Williams Fork formation	Lance formation	Vermejo formation	Laramie formation	Laramie formation	Pierre shale	Arapahoe fm. / Laramie fm. / Phantom s. / Milliken ss. m.	Laramie formation	Beecher Island sh. m.	Pierre shale	Pierre shale	Beecher Island shale memb. / Unnamed member / Soft Grass shale memb. / Lake Creek shale memb. / Weskan shale memb. / Sharon Springs shale memb.	Pierre shale	Niobrara fm. / Smoky Hill chalk memb.	Niobrara fm. / Smoky Hill chalk member / Fort Hays ls. m.	Niobrara formation
Mesaverde formation	Mesaverde formation		Price River form. / Castlegate ss. m. / Blackhawk fm. / Aberdeen ss. m. / Spring Canyon ss. / Storrs ls. m. / Panther Canyon ss.	Farrer fm. / Sulphur Cr. ss. m. / Thompson Cr. ss. m. / Alkali Cr. ss. m. / Sego ss. / Neslen form. / Mesaverde group	Mesaverde group / Rim Rock ss.	McDermott fm. / Kirtland sh. / Farmington ss. / Fruitland form. / Pictured Cliffs ss. / Lewis shale / Cliff House ss. / Menefee form. / Point Lookout ss.		Mesaverde group / Heater Can. fm. / Mount Garfield formation / Sego ss. / Kester Mbr.	Mesaverde group / Poonia sh. m. / Rollins ss. m.	Mesaverde group / Iles form. / Williams Fork form. / Trout Ck. s.m. / Rim Rock s.m.	Mesaverde group / Williams Fork formation / Iles(?) formation / Sandstone member	Mesaverde group / Iles form. / Trout Creek ss. / Mount Morris fm. / Milner Ss. / Hayden's Gulch fm. / Haybro fm. / Morapos ss. m.	Trinidad ss. / "Transition zone" / "Tepee Butte zone" / "Baculite zone" / "Rusty zone" / "Barren zone"	Fox Hills ss. / "Transition zone" / "Cone-in-cone zone" / "Tepee Butte zone" / "Rusty zone" / "Barren zone"	Fox Hills ss.	Fox Hills ss. / Transition sand / "Cone-in-cones z." / Unnamed unit / "Tepee Butte zone" / "Rusty zone" / "Barren zone"	Beecher Island sh. m.						
Masuk shale memb. / Emery ss. memb. / Blue Gate shale member	Masuk shale memb. / Emery ss. memb. / Blue Gate shale member		Emery ss. memb. / Bluecastle Tongue / Castlegate ss. memb.	Mancos shale	Mancos shale	Mancos shale	Mancos shale	Mancos shale	Mancos shale	Mancos shale	Mancos shale	Mancos shale	Niobrara fm. / Apishapa shale memb. / Timpas limestone memb. / Smoky Hill chalk memb. / Ft. Hays ls. mem.	Niobrara fm. / Apishapa shale member / Timpas limestone member	Pierre shale / Niobrara formation	Pierre shale / Niobrara formation	Pierre shale / Richards ss. m. / Larimer ss. m. / Rocky Ridge s. m. / Terry ss. m. / Hygiene ss. m. / Sharon Springs member / Niobrara fm. / Apishapa shale member / Timpas limestone member	Pierre shale / Niobrara formation / Smoky Hill marl member / Fort Hays ls.m.	Pierre shale / Niobrara formation / Smoky Hill marl member / Fort Hays ls.m.	Pierre shale / Niobrara fm. / Smoky Hill marl member / Fort Hays ls.m.				
Ferron sandstone member / Tununk shale member	Ferron sandstone member / Tununk shale member	Sandy member	Ferron ss. memb. / Dakota sandstone	Sandy unit	Frontier ss. memb. / Aspen shale memb.	Thin sandy mem. / Thin limestone m.	Thin sandy mem.	Thin sandy mem.	Sandy memb.	Sandy memb.	Sandstone m.	Sandstone m.	Codell ss. m. / 34a / Fairport chalky m. / Bridge Creek ls. m. / Hartland sh. / Lincoln ls. m. / Thatcher ls. / Greenhorn ls. / Graneros shale	Codell ss. / Greenhorn ls. / Graneros shale	Sandy ls. mem. / Dark shale member / Gray shale and limestone m. / Dark shale member	Sandstone and shale member / Sandy shale member / Light-colored sh. and ls. memb. / Dark shale member	Colorado group / Carlile sh. / Codell ss. m. / Fairport chalky sh. m. / Greenhorn ls. / Graneros shale	Benton shale / Calcareous member / Noncalcareous member	Benton shale / Shale and limestone member / Bleck shale member	Graneros sh.	Benton shale / Calcareous member / Noncalcareous member	Graneros shale / Carlile sh. / Codell ss. m. / Blue Hill sh. m. / Fairport chalky sh. m. / Bridge Creek limestone m. / Hartland sh. m. / Lincoln ls. m.	Graneros shale / Carlile sh. / Codell ss. m. / Fairport chalky sh. m. / Fleming sh. m. / Beloma chalk m. / Hartland sh. m. / Lincoln ls. m. / Graneros sh.	Graneros shale / Carlile shale / Greenhorn limestone / Upper shale member
Dakota ss.	Dakota ss.	Dakota sandstone	Dakota sandstone	Dakota ss.	Dakota sandstone	Dakota sandstone	Dakota sandstone	Dakota sandstone	Dakota sandstone	Dakota sandstone	Dakota sandstone	Bluish white sh. (Aspen)	Bluish white shale memb.	Dakota ss.	Dakota sandst.	Dakota sandstone	Upper quartzite m. / Shale member / Lower quartzite m.	Upper ss. m.	Upper brown ss. m. / Dark shale m. / Middle ss. m. / Second ss. m.	First ss. mem. / Shale memb. / Second ss. m.	First sandstone / Shale memb. / Second ss. m.	Dakota ss.	Cockrum ss.	Dakota ss.	Dakota ss.	Dakota ss.
Aspen shale (Unit R-2)																										
Dear River fm. (Unit R-3)																										
Wasatch fm. / Reddish and brownish shales and white sandstones / Ephraim conglomerate				Cedar Mountain shale / Buckhorn conglomerate		Shale and sandstone member / Congl. sandstone memb.	Coal-bearing member	Burro Canyon formation	Coal-bearing member	Burro Canyon formation	Coal-bearing member	Burro Canyon formation	Shale and sandstone member / Conglomeratic sandstone member	Shaly member / Conglomeratic sandstone member	Shaly member / Sandstone and conglomerate member		Highly colored shale / Conglomeratic sandstone	Third sandstone member	Sandstone and shale member							
Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Paleozoic	Jurassic	Jurassic	Paleozoic	Paleozoic	Paleozoic(?)	Paleozoic
31, 292, 332, 345	105, 114, 143	8, 115	35, 110, 152, 193, 289, 309	97	14, 101, 322–324, 335	245, 372	51, 310	90, 309, 310	84, 169, 331	126	250, 279	34, 279	15, 107, 137–139	95, 166	151, 198, 299, 340	19, 132, 187	118, 171, 189, 201, 215	166, 334	201, 237, 334	13, 55, 226	803	85, 334	329	12, 235, 265	48	329

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 63, PP. 1011-1044, 2 FIGS.; 1 PL. OCTOBER 1952

CORRELATION OF THE CRETACEOUS FORMATIONS OF THE WESTERN INTERIOR OF THE UNITED STATES

BY WILLIAM A. COBBAN AND JOHN B. REESIDE, JR.

CONTENTS

TEXT

	Page
Introduction	1011
Boundaries and major divisions of the Cretaceous	1012
Historical background of classification used	1014
Standard reference sequence	1015
Suggested zonal indices and other fossils	1015
Broad faunal relations	1022
Annotations	1026
Index by columns of stratigraphic names	1031
References cited	1034

ILLUSTRATIONS

Figure	Page
1. Generalized map of outcrop areas of Cretaceous sedimentary rocks in the Western Interior of the United States	1012
2. Index map showing areas represented by numbered columns of Chart 10b	1013

Plate	Facing Page
1. Correlation of the Cretaceous formations of the Western Interior of the United States (Chart 10b of series)	1011 and 1043

INTRODUCTION

This is Number 10b of a series of correlation charts of North American sedimentary formations prepared by the Committee on Stratigraphy of the National Research Council (Dunbar, 1942).

The compilers of this chart have attempted to show, as nearly completely as is reasonably possible, the present state of classification and nomenclature of the Cretaceous formations in the Western Interior of the United States, chiefly in Arizona, New Mexico, Utah, Colorado, Kansas, Wyoming, Nebraska, Iowa, Montana, the Dakotas, and Minnesota. The generalized map (Fig. 1), after Stose (1946), indicates the major areas of outcrop in the region. The index map (Fig. 2) shows by number the general location of each area represented by a column of the chart (Pl. 1). Columns are given in Plate 1 for 128 areas, arranged by States, and, within each State, from south to north and from west to east. Each column includes the stratigraphic units recognized in the area.

Some 315 stratigraphic names, of various ranks, are noted in the chart, and an index of them referred to column numbers is given at the end of the paper. Some of the names used in earlier publications have long since been displaced and are not considered here. They may be found in Wilmarth's *Lexicon of geologic names* (1938). In some columns variant parallel nomenclatures are shown. Probably some of the later names have been overlooked, but the compilers doubt that many such would be of major importance. In the index and in the chart the source area of the name (typical occurrence) of a stratigraphic unit is indicated by an asterisk (*). Chronologic relations are indicated by horizontal position. Hiatuses are indicated by vertical lining; lack of knowledge, through nonexposure or other cause, is indicated by diagonal lining. Numbers within the columns of the chart refer to annotations given here. The chief sources for the data given are shown by reference numbers at the bottom of each column. (*See* References Cited). Abbreviations used in the chart are as follows:

bent.	bentonite
chk.	chalk
chy.	chalky
cong., congl.	conglomerate
f., fm., form.	formation
forms.	formations

gr.	group
ls.	limestone
m., mem., memb.	member
pt.	part

compilers here express their obligation to their colleagues for this assistance. Special credit is due T. W. Stanton for information used in

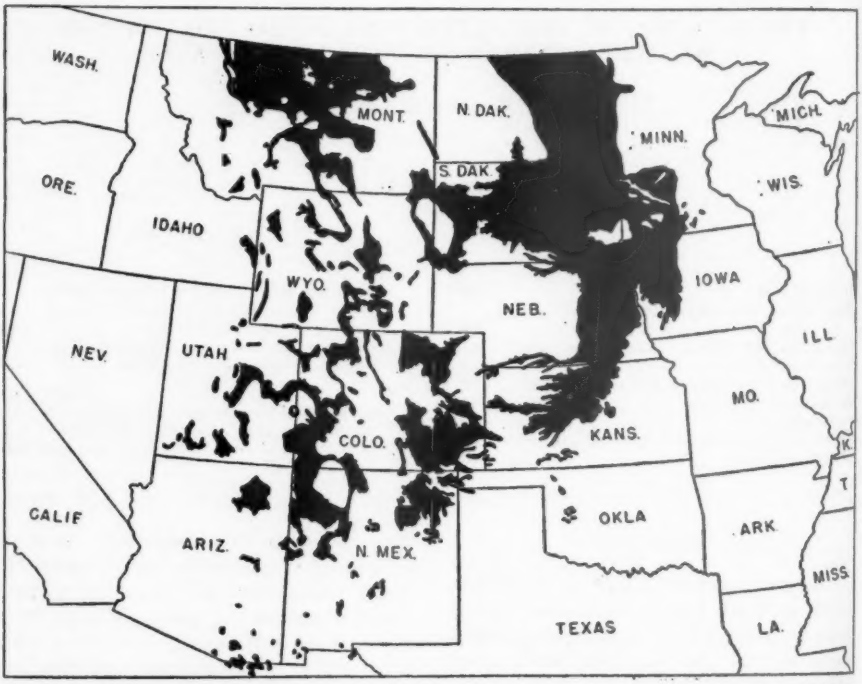


FIGURE 1.—GENERALIZED MAP OF OUTCROP AREAS OF CRETACEOUS SEDIMENTARY ROCKS IN THE WESTERN INTERIOR OF THE UNITED STATES

s., ss., sand.	sandstone
sdy.	sandy
sh.	shale
t., ton., tong.	tongue
up.	upper
z.	zone

The compilers have visited many of the areas considered and have found the first-hand acquaintance with them very useful in examining the voluminous literature of the region. The accumulated fossil collections of the U. S. Geological Survey and the U. S. National Museum have also provided much useful local information. In addition to these data, many associates, by discussions in the field and in the office and by written communications, have supplied unpublished data. It has not been possible to acknowledge individually all such information, and the

Column 10, W. W. Rubey for Columns 65 and 66, and R. K. Hose for Column 78.

BOUNDARIES AND MAJOR DIVISIONS OF THE CRETACEOUS

Muller and Schenck in 1943 discussed the Cretaceous system of the World at some length and provided an extensive bibliography of literature pertinent to the history of the term, the subdivisions, and other aspects of the unit. The present notes deal only with more local aspects of some of these matters.

The lower boundary of the Cretaceous system is placed very precisely where marine strata assigned by general agreement to the earliest part of the Berriasian stage rest upon marine strata similarly assigned to the latest

part of the Tithonian stage, as in the western Alps. In many regions, however, no such precision is possible, for some of the beds may be nonmarine or unfossiliferous or otherwise

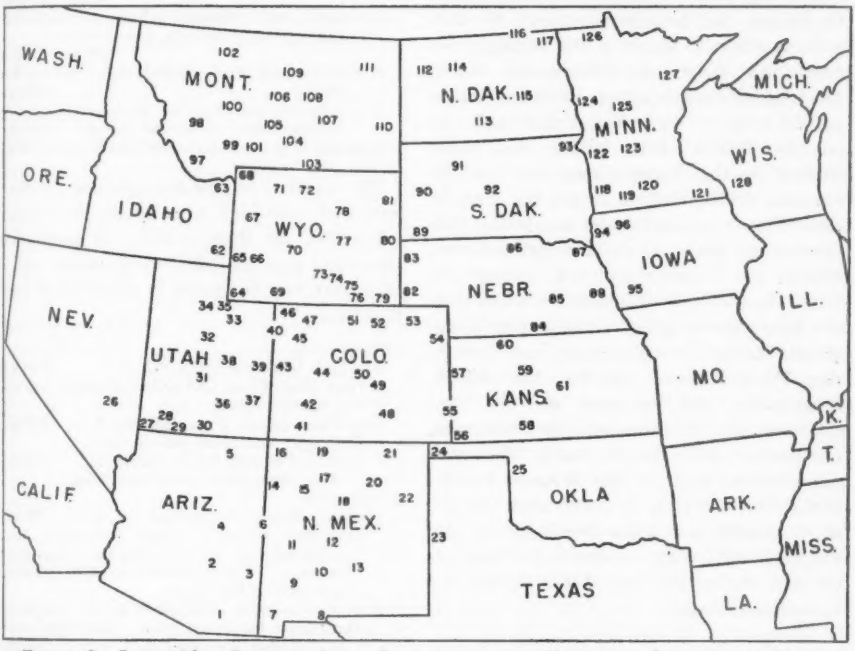


FIGURE 2.—INDEX MAP SHOWING AREAS REPRESENTED BY NUMBERED COLUMNS OF PLATE 1 (CHART 10B)

difficultly assignable, and opinions may differ for each region concerning the position of the boundary. In the Western Interior of the United States the establishment of the boundary between the Jurassic and the Cretaceous systems was long controversial (Baker and others, 1906, p. 58–63), primarily because of a vigorous disagreement as to the age of the Morrison formation. There is now fairly general agreement that the Morrison is Jurassic and that the next overlying beds are Cretaceous. At many places there is little doubt where a boundary is to be drawn. At many other places, however, a fairly uniform sequence of deposits cannot be satisfactorily dated or can be dated only as Jurassic below and Cretaceous above, with no indisputable plane of separation between them; in these places either an arbitrary spearation has to be made or an interval left unassigned.

The upper boundary of the Cretaceous system is much less securely established than the lower boundary. Customarily the Danian stage is assigned the highest position in the Cretaceous, but opinions differ as to what beds are to be correlated with the typical Danian, and whether the typical Danian is really Cretaceous. For the Western Interior the compilers have arbitrarily included the Danian in the Cretaceous and have placed it at the level of the *Triceratops*-bearing beds. These beds, like the Morrison formation, were the subject of a long controversy. There seems now to be general acceptance of the thesis that the overlying beds, in North Dakota and South Dakota containing the marine Cannonball fauna (Stanton, 1920; Fox, 1942) and elsewhere containing primitive mammals and no dinosaurs, are to be assigned to the Paleocene. In practice the criteria may be locally somewhat difficult to apply, and in some regions

there are sedimentary units that, in whole or in part, cannot be assigned with assurance.

Within the Cretaceous, the most widely adopted practice is to divide the system into two series, Lower and Upper (Spath, 1941). In Europe the boundary between the two series is generally placed at the boundary between the Albian and Cenomanian stages. The most common departures from this custom are the usage of many British geologists who put the British Gault (middle and upper Albian) in the Upper Cretaceous (as, for example, Arkell, 1947, p. 2) and the usage of some French geologists who divide the Cretaceous into three parts and recognize Lower, Middle, and Upper series (as, for example, in Émile Haug's *Traité de Géologie*, in which work the Eocretaceous group includes the Valanginian, Hauterivian, Barremian, and Aptian; the Mesocretaceous includes the Albian, Cenomanian, and Turonian; and the Neocretaceous includes the Coniacian, Santonian, Campanian, and Maestrichtian). The compilers believe that, for the Western Interior of the United States, the more usual practice of recognizing two series should be adopted and we should attempt to identify the boundary between the equivalents of the Albian and Cenomanian stages.

Historical Background of Classification Used

C. A. White (1891) has sketched the history of the earlier exploration and interpretation of the Cretaceous rocks of the Western Interior as part of his general account of the Cretaceous system in North America. Much detail concerning the nomenclature up to the end of 1936 is given by Wilmarth (1938). No inclusive discussion of the American Cretaceous has been published since that work.

The earliest published records of the Cretaceous in the Western Interior, dating back to the first decade of the nineteenth century, are primarily paleontologic and are little concerned with stratigraphic nomenclature. It was not until 1856 that F. B. Meek and F. V. Hayden, as a result of their expedition to the Missouri Valley for James Hall, proposed a general classification as follows:

"Tertiary.
Cretaceous system.
5. Gray and yellowish arenaceous clays containing great numbers of marine mollusca with a few land plants. 100 to 150 feet.
4. Plastic clays with numerous marine mollusca. About 350 feet.
3. Grayish and yellowish calcareous marl, containing *Ostrea congesta*, fish scales, etc. 100 to 150 feet.
2. Grayish and lead colored clays having few fossils. 80 feet.
1. Sandstones and clays not positively known to belong to the Cretaceous system. 90 feet.
Limestones of upper coal measures at Council Bluffs.

The numbers for the stratigraphic divisions were used until 1861, when Meek and Hayden substituted for them a series of geographic terms and gave an extended discussion and a table that may be quoted in abbreviated form as follows:

"Upper series
Fox Hills beds. Formation No. 5 500 feet
Gray, ferruginous and yellowish sandstone and arenaceous clays, . . .
Fort Pierre group. Formation No. 4. 700 feet
Dark gray and bluish plastic clays, . . .
Dark bed of very fine unctuous clay, . . . Local; filling depressions in the bed below.
Lower series
Niobrara division. Formation No. 3. 200 feet
Lead-gray calcareous marl, weathering to a yellowish or whitish chalky appearance above. . . . Passing down into light, yellowish and whitish limestone. . . .
Fort Benton group. Formation No. 2. 800 feet
Dark gray laminated clays, sometimes alternating near the upper part with seams and layers of soft gray and light-colored limestone. . . .
Dakota group. Formation No. 1. 400 feet
Yellowish, reddish, and occasionally white sandstone, with, at places, alternations of various colored clays and beds and seams of impure lignite. . . .

Meek and Hayden considered their "Lower series" equivalent to the "Lower or Gray Chalk (and Upper Greensand) of British geologists (*Turonien* and *Cenomanien?* of D'Orbigny)," and their "Upper series" equivalent to the "Upper or White Chalk and Maestricht beds (*Senonien* of D'Orbigny)." With little modification the Meek and Hayden section is still the basic framework of a standard reference section for the Western Interior.

The nonmarine rocks immediately overlying the Fox Hills sandstone, considered Tertiary by Meek and Hayden, were the subject of a long controversy that only in recent years seems to have reached a generally acceptable

solution. The nonmarine beds are considered now to be in part Tertiary and in part Cretaceous, the boundary between them and the names applied being chosen on the basis of local features.

As information accumulated over the years, many names, dictated by local development of lithologic facies, have been applied to subordinate divisions of the Cretaceous. Meek and Hayden's "Lower series," modified by the exclusion of the "Dakota group," became in 1878 the Colorado group (White, 1878, p. 21, 22, 30), and their "Upper series" became in 1888 the Montana group (Eldridge, 1888, p. 3). Both these names have had wide application and are still very useful inclusive terms. In the first studies of some areas, local names were applied that proved to be less serviceable than names originally applied elsewhere, and the local names have passed out of use in favor of the other names. The net results, for nomenclature and correlation, of nearly a century of geologic study since the beginning of the Meek and Hayden work constitute the classification shown in Plate 1.

Standard Reference Sequence

A standard reference sequence for the Western Interior is shown near the left margin of Plate 1.

As indicated in Historical Background of Classification Used, the first sequence of lithologic units described and named was that for the Missouri Valley. As it is an entirely marine sequence, it has become the basis of a convenient standard of reference. Continued study of the Cretaceous deposits has naturally added much detail and has dictated the subdivision of Meek and Hayden's units and the addition of certain units to the standard.

In their section Meek and Hayden described their "Fort Pierre group" as filling depressions in the top of their "Niobrara division," implying a discontinuity between their "Nos. 3 and 4." It has become evident that the hiatus represented by the discontinuity was filled farther west by the Telegraph Creek and Eagle formations, and these units have been added to the standard sequence.

Meek and Hayden's original "Fort Benton group" was named for exposures in Montana supposed to be equivalent to "No. 2" of the lower Missouri Valley. Actually these exposures include both "No. 2" and "No. 3" of the lower valley. Usage has, however, effectively restricted the name Benton, as Meek and Hayden intended, to "No. 2." Gilbert in 1896 (p. 564) found it convenient in eastern Colorado to divide the Benton group into three formations—the Graneros shale below, the Greenhorn limestone in the middle, and the Carlile shale above. These names have been widely used over the Great Plains region, but it seems desirable now to modify the scope of the Greenhorn from that of Gilbert's definition and to replace the Graneros in the standard reference sequence by the less equivocal Belle Fourche shale.

In the western Black Hills the Belle Fourche shale is underlain by the Mowry shale, the Newcastle sandstone, the Skull Creek shale, and the Fall River sandstone. The recent recognition by the compilers (1951) of the ammonite genera *Gastroplites* and *Neogastroplites* in the Mowry shale shows that this formation is very late Early Cretaceous. The Skull Creek shale contains a marine fauna and appears to be equivalent to the Purgatoire formation of Colorado and the Kiowa shale of Kansas. As these or equivalent units are widespread, it has seemed appropriate to include them in the standard sequence.

For the still earlier part of the sequence, no unit except the Gannett group of southeastern Idaho and the adjacent part of Wyoming seems to cover the interval. The two limestones, the Peterson and Draney, in the middle part of the group contain a fresh-water fauna like the faunas of the Cloverly and Kootenai formations, with the Ephraim conglomerate below and an unnamed red shale above. With some hesitation the compilers suggest this group as part of the reference sequence, in spite of its relative remoteness from the remainder of the reference sequence.

Suggested Zonal Indices and Other Fossils

The compilers present, near the left margin of Plate 1, a column of some 30 faunal names, which are suggested as zonal indices, and also a diagram indicating the ranges of certain important species of invertebrates, chiefly

mollusks. The ammonoids, as in other regions, are the most useful forms, particularly the scaphites and the baculites, both of which are found in abundance and variety, as well as in many kinds of sediment. Among the pelecypods the species of *Inoceramus* are abundant and varied. As parts of the Cretaceous sequence are nonmarine, especially toward the west, some of the nonmarine species are useful markers.

For reasons not well understood, the corals, the echinoderms, the brachiopods, the bryozoans, and the crustaceans are relatively rare and of little value for correlation. Some of the molluscan groups are likewise relatively rare, such as the rudistids and the belemnoids.

The compilers believe that certain groups of fossil organisms have not yet been worked out in the region to the point where they are widely useful as close indices, and no attempt has been made to include them in the paleontologic part of the chart. Among these are the marine ostracodes, the foraminifers, the plants, and the vertebrates. These organisms, when adequately studied, will undoubtedly be as useful as any others.

The following discussion considers the suggested zones in order from bottom to top and offers notes on some of the associated fossils and on the geographic distribution of the zones.

UNDETERMINED ZONE: The lowest part of the Cretaceous sequence in the Western Interior is apparently represented in the Ephraim conglomerate of the Gannett group of eastern Idaho and adjacent parts of Wyoming. Whether the lower part of the Ephraim includes Jurassic deposits is not determined. No satisfactory fossils have been found in this interval, and no zonal indicators are suggested. Over large areas, especially in the Great Plains, this interval is probably not represented by sediments.

ZONE OF *Protelliptio douglassi* (STANTON): The interval of the Peterson and Draney limestones and their equivalents, such as parts of the Cloverly formation and of the Kootenai formation (of Montana), is marked by *Protelliptio douglassi* (Stanton) (1903, p. 195). It is associated with *Unio farri* Stanton (1903, p. 194), *Stantonogyra silberlingi* (Stanton) (1903, p. 198), *Campeloma harlowtonensis* Stanton (1903, p. 196), and *Quadrula natosini* (McLearn) (1929, p. 73). Peck (1941, 1951) reports nonmarine ostracodes from this zone: *Pseudocypridina inornata* (Peck), *Cypridea anomala* Peck, *C. compta* Peck, and *C. wyomingensis* Jones; and charophyte oogonia: *Atopochara trivolvis* Peck and *Clavator harrisi* Peck. This nonmarine fauna is known in western Colorado, across Wyoming and Montana, and at an isolated locality in Nevada.

UNDETERMINED ZONE: A time interval in the later Early Cretaceous, immediately before deposition of the Skull Creek shale and its equivalents, is probably only in part represented by sediments in the Western Interior. These sediments have not furnished fossils that would seem useful as zonal indicators, and none is suggested.

ZONES OF *Oxytropidoceras* STIELER AND OF *Inoceramus comancheanus* CRAGIN: The Skull Creek shale and its equivalents are marked by *Inoceramus comancheanus* Cragin (Reeside, 1923a, p. 202). It is associated with *Inoceramus bellvuensis* Reeside (1923a, p. 203). In the Kiowa formation of Kansas a large fauna, including the ammonite genus *Oxytropidoceras* Stieler, is present in this zone (Twenhofel, 1924). The nonmarine Bear River fauna is represented in the western marginal deposits of this interval, including such species as *Unio bellaplicatus* Meek (White, 1895, p. 34), *Ursirivus pyriformis* (Meek) [= *Corbula pyriformis* Meek (White, 1895, p. 38)], *Pygulifera humerosa* Meek (White, 1895, p. 55), and *Campeloma macrospira* Meek (White, 1895, p. 60). Peck (1951) reports in this zone the nonmarine ostracodes *Pseudocypridina laevicula* Peck and *Cypridea skeeteri* Peck. The marine facies is especially well shown in Kansas, but the fauna can be followed with progressive restriction into the Purgatoire formation of eastern Colorado, the Skull Creek shale of the Black Hills, and the basal part of the Colorado shale of Montana.

ZONE OF *Gastroplites* MCLEARN: The lower part of the Mowry shale and its equivalents are marked by the ammonite genus *Gastroplites* McLearn (1933, p. 14). The zone may also include the equivalents of the Newcastle sandstone, but the diagnostic fossils have not been found in them. The zone contains the lower part of the ranges of *Metengonoceras* Hyatt (1903, p. 179), *Ostrea anomioides* Meek (Stan-

ton, 1893, p. 55), *Nemocardium* aff. *N. kansasense* (Meek) (1876, p. 170), and *Bicorbula dubiosa* (White) (1879b, p. 249). The nonmarine Bear River formation occupies the interval immediately below the *Gastroplites* zone, but its fauna in part reappears in the marginal facies of the Aspen formation, and the upper part of the ranges of some of the nonmarine species is shown on this chart as extending into the lower part of the *Gastroplites* zone.

ZONE OF *Neogastroplites* MCLEARN: The upper part of the Mowry shale and its equivalents contain ammonites of the genus *Neogastroplites* McLearn (1933, p. 21). It is associated with *Inoceramus nahwisi* McLearn (1931, p. 7). The zone contains the upper part of the ranges of *Ostrea anomioides* Meek, *Nemocardium* aff. *N. kansasense* (Meek), *Bicorbula dubiosa* (White), and *Metengonoceras* Hyatt. This zone is recorded particularly from Wyoming and Montana.

ZONE OF *Calycoceras* HYATT: In eastern Colorado the lower part of the Graneros shale, in northwestern Colorado the upper part of the Dakota sandstone, and in central Wyoming part of the Frontier formation have yielded the characteristic Cenomanian genus *Calycoceras* Hyatt [= *Metacalycoceras* Adkins, 1928, p. 241)]. These beds are equivalent to the lower part of Belle Fourche shale; and it is believed that this interval, though commonly barren, will elsewhere furnish diagnostic species. It is not known whether *Brachydontes multilinigera* (Meek) Stanton, (1893, p. 86) ranges below this zone, although similar forms are known at lower levels.

ZONE OF *Acanthoceras? amphibolum* MORROW: The middle zone in the Belle Fourche shale and its equivalents is marked by *Acanthoceras? amphibolum* Morrow (1935, p. 470). The zone includes the lowest part of the range of *Turritella whitei* Stanton (1893, p. 130) and is well developed in Kansas, eastern Colorado, Wyoming, and Montana.

ZONE OF *Acanthoceras?* SP. A: The uppermost part of the Belle Fourche shale and its equivalents are marked by a readily recognizable ammonite that at present has no formal name, but for convenience of reference is here called *Acanthoceras?* sp. A. This zone includes the lowest part of the ranges of *Ostrea soleniscus* Meek (Stanton, 1893, p. 56) and *Cardium pauperculum* Meek (Stanton, 1893, p. 99). This zone is well developed in Wyoming and Montana.

ZONE OF *Dunveganoceras pondi* HAAS: In central Wyoming rocks equivalent to the lowest member of the Greenhorn formation, the Lincoln limestone member, are marked by *Dunveganoceras pondi* Haas (1949, p. 22). It is associated with *Mantelliceras canitaurinum* Haas (1949, p. 9), *Metoicoceras praecox* Haas (1949, p. 15), and *Inoceramus prefragilis* Stephenson (1952, p. 64). The zone includes the lower part of the ranges of *Exogyra columbella* Meek (Stanton, 1893, p. 63) and *Pseudomelania hendricksoni* Henderson (1934, p. 262), and, farther south, of *Exogyra olisiponensis* Sharpe (Reeside, 1929b, p. 268), *Ostrea prudentia* White (Stanton, 1893, p. 54), and *Gryphaea newberryi* Stanton (1893, p. 60).

ZONE OF *Dunveganoceras* aff. *D. albertense* (WARREN): In central Montana and northern Wyoming rocks equivalent to the second member of the Greenhorn formation, the Hartland shale member, are marked by an unnamed species of *Dunveganoceras* closely related to *D. albertense* (Warren) (1940, p. 149). The zone includes the higher part of the ranges of *Exogyra columbella* Meek and *Pseudomelania hendricksoni* Henderson and, farther south, of *Exogyra olisiponensis* Sharpe, *Ostrea prudentia* White, and *Gryphaea newberryi* Stanton.

ZONE OF *Sciponoceras gracile* (SHUMARD): The third member of the Greenhorn formation, the Jetmore chalk, and its equivalents are marked by *Sciponoceras gracile* (Shumard) [= *Baculites gracilis* Shumard (Stanton, 1893, p. 166)]. It is associated with *Scaphites delicatulus* Warren (1930, p. 66), "*Worthoceras*" Adkins (1928, p. 218), and *Metoicoceras whitei* Hyatt (1903, p. 122). The zone includes the highest part of the range of *Inoceramus prefragilis* Stephenson and the lowest part of the ranges of *Tragodesmoceras* Spath (Morrow, 1935, p. 468), *Watinoceras* Warren (1930, p. 66) [see also *Acanthoceras? coloradoense* Henderson (1908, p. 259)], and *Neocardioceras* Spath [Adkins, 1931, p. 72. See also *Acanthoceras? kanabense* Stanton (1893, p. 181)]. *Sciponoceras* is the oldest baculitid recorded from the Western Interior. The zone is widely distributed in the Great Plains and the Colorado Plateaus.

ZONE OF *Inoceramus labiatus* SCHLOTHEIM: The uppermost member of the Greenhorn formation, the Pfeifer limestone, and its equivalents are marked by *Inoceramus labiatus* Schlotheim (Stanton, 1893, p. 77). It is associated with *Thomasites* Pervinquière (1907) and *Vascoceras* Choffat (Reeside, 1923b, p. 28). This zone includes the highest part of the ranges of *Watinoceras* Warren and *Neocardioceras* Spath and the lowest part of the range of *Inoceramus fragilis* Hall and Meek (1856, p. 388); it is very widely distributed.

ZONE OF *Collignoniceras woollgari* (MANTELL): The lowest member of the Carlile shale, the Fairport chalky shale, and its equivalents are marked by *Collignoniceras woollgari* (Mantell) [= *Prionotropis woollgari* of Meek (1876, p. 455)]. It is associated with *Scaphites larvaeformis* Meek and Hayden (Meek, 1876, p. 418). The zone includes the highest part of the range of *Tragodesmoceras* Spath and the lowest part of the ranges of *Baculites* cf. *B. besairiei* Collignon (1931, p. 37) and *Gyrodes conradi* Meek (Stanton, 1893, p. 136). This zone is widely distributed.

ZONE OF *Collignoniceras hyatti* (STANTON): The second member of the Carlile shale, the Blue Hill shale, and its equivalents are marked by *Collignoniceras hyatti* (Stanton) [= *Prionotropis hyatti* Stanton (1893, p. 176)]. It is associated with *Scaphites carlilensis* Morrow (1935, p. 466) and it includes the higher part of the range of *Inoceramus fragilis* Hall and Meek. The "*Pugnellus* sandstone" of the older literature (Stanton, 1893, p. 28) is part of this zone. This zone is widely distributed in the Great Plains and in eastern Utah.

ZONE OF *Scaphites warreni* MEEK AND HAYDEN: The lower part of the third member of the Carlile shale, the Turner sandy member, and its equivalents are marked by *Scaphites warreni* Meek and Hayden (Cobban, 1951c, p. 21). It is associated with *Prionocyclus macombi* Meek (Stanton, 1893, p. 172) and *Inoceramus dimidius* White (Stanton, 1893, p. 78). The zone includes the lower part of the ranges of *Ostrea lugubris* Conrad (Stanton, 1893, p. 58), *O. malachitensis* Stanton (1893, p. 57), and *Pholadomya coloradoensis* Stanton (1893, p. 116). This zone is known around the Black Hills, eastern Wyoming, western Colorado, eastern Utah, and northern New Mexico.

ZONE OF *Prionocyclus wyomingensis* MEEK: The middle part of the Turner member of the Carlile shale and its equivalents are marked by *Prionocyclus wyomingensis* Meek (Stanton, 1893, p. 171). It is associated with *Scaphites ferronensis* Cobban (1951c, p. 23) and *S. whitfieldi* Cobban (1951c, p. 24). The zone includes the higher part of the ranges of *Ostrea lugubris* Conrad, *O. malachitensis* Stanton, and *Pholadomya coloradoensis* Stanton, and the lower part of the range of *Inoceramus perplexus* Whitfield (1880, p. 392). This zone is widely but irregularly distributed. In New Mexico, Utah, and Colorado it is possible to divide this zone into a lower part with *Scaphites ferronensis* and an upper part with *Scaphites whitfieldi*.

ZONE OF *Scaphites nigricollensis* COBBAN: The upper part of the Turner member of the Carlile shale and its equivalents are marked by *Scaphites nigricollensis* Cobban (1951c, p. 25). It is associated with *Prionocyclus reesidei* Sidwell (1932, p. 318). The zone includes the upper part of the range of *Inoceramus perplexus* Whitfield and is widely distributed in the northern Great Plains.

ZONE OF *Scaphites corvensis* COBBAN: The uppermost member of the Carlile shale, the Sage Breaks member, and its equivalents are marked by *Scaphites corvensis* Cobban (1951c, p. 26). The zone includes the highest part of the range of *Baculites* cf. *B. besaireii* Collignon and the lowest part of the range of *Ostrea congesta* Conrad (Meek, 1876, p. 13) Near the western margin of deposition nonmarine deposits of this age contain "*Cyrena*" *carletoni* (Meek) (White, 1883b, p. 436), *Neritina bellatula* Meek (White, 1883b, p. 458), and *Physa carletoni* Meek (White, 1883b, p 43). This zone is known only in the northern Great Plains.

ZONE OF *Inoceramus deformis* MEEK: The lower member of the Niobrara formation, the Fort Hayes limestone, and its equivalents are marked by *Inoceramus deformis* Meek (Stanton, 1893, p. 85). It is associated with *Scaphites Inoceramus deformis* Meek (Stanton, 1893, p. 85). It is associated with *Scaphites impendicostatus* Cobban (1951c, p. 28), *S. preventricosus* Cobban (1951c, p. 26), *Baculites mariasensis* Cobban (1951b, p. 818), *Barroisiceras* Grossouvre (Reeside, 1932), *Inoceramus erectus*

Meek (1877, p. 145), *Veniella goniophora* Meek (1876, p. 152), *Ostrea sannionis* White (1884, p. 300), and *Cardium curtum* Meek and Hayden (Meek, 1877, p. 151). It includes the lowest part of the range of *Binneyites* Reeside (1927b, p. 4). This zone is very widely distributed. In Montana, where the rocks equivalent to the Fort Hays limestone are characterized, by *Schaphites preventricosus*, a zone of *Inoceramus deformis*, s.s., can be recognized above a zone marked by small variants of *I. deformis* and *I. erectus*.

ZONE OF *Scaphites ventricosus* MEEK AND HAYDEN: The lowest part of the equivalents of the Smoky Hill chalk member of the Niobrara formation is marked by *Scaphites ventricosus* Meek and Hayden (Meek, 1876, p. 425). It is associated with *Inoceramus umbonatus* Meek and Hayden (Meek, 1876, p. 44). This zone includes the lowest part of the ranges of *Baculites asper* Morton (Reeside, 1927a, p. 13) and *Inoceramus grandis* (Conrad) [= *Haploscapha grandis* (Conrad, 1875, p. 23)]. This zone is widespread.

ZONE OF *Scaphites depressus* REESIDE: The second zone in the equivalents of the Smoky Hill member of the Niobrara formation is marked by *Scaphites depressus* Reeside (1927b, p. 7). It is associated with *Phlycticrioceras* Spath (Reeside, 1927b, p. 2), *Texanites shoshonensis* (Meek) [= *Mortoniceras shoshonense* Meek (Reeside, 1927b, p. 9)], and *Inoceramus stantoni* Sokolow [= *I. acuteplicatus* Stanton (1899, p. 634)]. It includes the lowest part of the range of *Baculites codyensis* Reeside (1927b, p. 4). This zone is widespread.

ZONE OF *Clioscaphites vermiformis* (MEEK AND HAYDEN): The third zone in the equivalents of the Smoky Hill member of the Niobrara formation is marked by *Clioscaphites vermiformis* (Meek and Hayden) [= *Scaphites vermiformis* Meek and Hayden (Meek, 1876, p. 423)]. This zone includes the highest part of the ranges of *Binneyites* Reeside, *Inoceramus grandis* (Conrad), and *Ostrea soleniscus* Meek and the lowest part of the range of *Uintacrinus* Grinnell (1876). In the south it includes the lowest part of the ranges of *Texanites omeraensis* (Reeside) [= *Mortoniceras omeraense* Reeside (1927a, p. 38)], *Placenticeras guadalupe* (Roemer) (Reeside, 1927a, p. 36), and *Inoceramus undulatoplicatus* Roemer (1852, p. 59). This zone is widespread.

ZONE OF *Clioscaphites choteauensis* COBBAN: The fourth zone in the equivalents of the Smoky Hill member of the Niobrara formation is marked by *Clioscaphites choteauensis* Cobban (1951c, p. 38). This zone is widespread.

ZONE OF *Desmoscaphites erdmanni* COBBAN: The uppermost zone in the equivalents of the Smoky Hill member of the Niobrara formation is marked by *Desmoscaphites erdmanni* Cobban (1951c, p. 38). It is the highest zone in the Colorado group and includes the highest part of the ranges of *Baculites codyensis* Reeside, *Ostrea congesta* Conrad, *Cardium pauperculum* Meek, *Turritella whitei* Stanton, and *Gyrodes conradi* Meek. It includes the lowest part of the ranges of *Baculites thomi* Reeside (1927b, p. 13) and *Inoceramus lundbreckensis* McLearn (1929, p. 77). In the south it includes the highest part of the ranges of *Texanites omeraensis* (Reeside), *Placenticeras guadalupe* (Roemer), and *Inoceramus undulatoplicatus* Roemer. This zone is best known in Montana but it is probably widespread.

ZONE OF *Desmoscaphites bassleri* REESIDE: The Telegraph Creek formation and its equivalents are marked by *Desmoscaphites bassleri* Reeside (1927a, p. 16). The zone contains the only recorded occurrences of the crinoid *Marsupites* (Thom, 1935, p. 55) in the Western Interior; it includes the highest part of the ranges of *Baculites thomi* Reeside and *Uintacrinus* Grinnell, and the lowest part of the ranges of *Baculites aquilaensis* Reeside (1927a, p. 12), *B. haresi* Reeside (1927a, p. 10), *Placenticeras planum* Hyatt (Reeside, 1927a, p. 31), *P. meeki* Boehm [= *P. whitfieldi* Hyatt (1903, p. 221)], *Ethmocardium* White (1880), and *Cymella montanensis* (Henderson) [= *Liopistha undata* (Meek and Hayden) (Meek, 1876, p. 236)]. Very rarely *Scaphites hippocrepis* (DeKay) (Reeside, 1927a, p. 22) is found in this zone, mostly in the upper part. No trace of this zone has been found east of the Black Hills, but it is widespread to the west.

ZONE OF *Scaphites hippocrepis* (DEKAY): The Eagle sandstone and its equivalents are marked by *Scaphites hippocrepis* (DeKay) and its varieties. Associated with it are *Scaphites aquilaensis* Reeside (1927a, p. 25) and *Haresiceras* Reeside (1927a, p. 17). The zone includes

the highest ranges of *Baculites asper* Morton, *Placenticeras planum* Hyatt, and *Inoceramus lundbreckensis* McLearn and the lowest ranges of *Ostrea russelli* Landes (1940, p. 139) and *Inoceramus "barabini* Morton" of Meek (1876, p. 49). No trace of this zone has been found east of the Black Hills, but it is widespread to the west.

ZONE OF *Baculites asperiformis* MEEK: The equivalents of the Sharon Springs member of the Pierre shale are marked by *Baculites asperiformis* Meek (1876, p. 405). Associated with it is *Inoceramus pertenuis* Meek and Hayden (Meek, 1876, p. 47). This zone includes the highest ranges of *Baculites aquilaensis* Reeside, *B. haresi* Reeside, and *Ostrea russelli* Landes and the lowest ranges of *Placenticeras intercalare* (Meek) (Hyatt, 1903, p. 207) and of *Acanthoscaphites* Nowak, s. l. This zone is widespread.

ZONE OF *Baculites gregoryensis* COBBAN: The Gregory and Crow Creek members of the Pierre shale and their equivalents are marked by *Baculites gregoryensis* Cobban (1951b, p. 820). Associated with it are *Pachydiscus complexus* (Hall and Meek) (Meek, 1876, p. 447), *Inoceramus oblongus* Meek (White, 1879a, p. 285), and *I. sublaevis* Hall and Meek, (1856, p. 386). The zone includes the lower part of the ranges of *Solenoceras* Conrad [= *Ptychoceras* of Meek (1876, p. 410)], *Didymoceras* Hyatt (1894, p. 573), *Emperoceras* Hyatt (1894, p. 575), and *Ostrea glabra* Meek and Hayden (Meek, 1876, p. 509), and, among the nonmarine species, *Goniobasis? subtortuosa* Meek and Hayden (Meek, 1876, p. 569), *G. judithensis* Stanton (Stanton *et al.*, 1905, p. 117), and *Brachydontes laticostata* White (1883b, p. 423). This zone is widespread; it passes westward into nonmarine units such as the Judith River formation.

ZONE OF *Baculites compressus* SAY: The DeGrey, Verendrye, and Virgin Creek members of the Pierre shale and their equivalents are marked by *Baculites compressus* Say, s. l. (Meek, 1876, p. 400). Associated with it are *Acanthoscaphites nodosus* (Owen), s. l. (1852, p. 581), *Rhaeboceras* Meek (1876, p. 462), and *Exiteloceras* Hyatt [= *Ancyloceras* of Whitfield (1880, p. 452)]. In the upper part of this zone are found *Acanthoscaphites brevis* (Meek) (1876, p. 426) and *A. quadrangularis* (Meek and Hayden) (Meek, 1876, p 428). In the lower part is found *Pholadomya hodgei* (Meek) (Meek, 1876, p. 219) and *Baculites pseudovatus* Elias (1933, p. 304). The zone includes the higher part of the ranges of *Placenticeras meeki* Boehm, *P. intercalare* (Meek), *Solenoceras* Conrad, *Emperoceras* Hyatt, *Didymoceras* Hyatt, *Inoceramus "barabini* Morton" of Meek, *Cymella montanensis* (Henderson), and the nonmarine *Goniobasis judithensis* Stanton. The zone includes the lowest part of the ranges of *Inoceramus sagensis* Owen (1852, p. 582) and, near the top, of *Veniella humilis* (Meek and Hayden) (Meek, 1876, p. 155); it also contains the only recorded occurrence in Western Interior of *Exogyra costata* Say (Reeside, 1929b, p. 271). This zone is widespread.

ZONE OF *Baculites baculus* MEEK AND HAYDEN: The lowest part of the Mobridge member of the Pierre shale is marked by *Baculites baculus* Meek and Hayden (Meek, 1876, p. 397). It may also contain *Acanthoscaphites plenus* (Meek and Hayden) (Meek, 1876, p. 429). This zone includes the highest part of the known range of the genus *Ethmocardium* White and the lowest part of the ranges of *Inoceramus fibrosus* (Meek and Hayden) [= *Pteria fibrosa* (Meek, 1876, p. 36)] and *"Belemnitella bulbosa* Meek and Hayden" (Meek, 1876, p. 504). This zone is widespread in the Great Plains.

ZONE OF *Baculites grandis* HALL AND MEEK: Most of the Mobridge member of the Pierre shale is marked by *Baculites grandis* Hall and Meek (1856, p. 402). The zone includes the higher part of the ranges of *Inoceramus fibrosus* (Meek and Hayden) and *Inoceramus sagensis* Owen and to the west, where sandstones appear, the lowest occurrences of *Sphenodiscus* Meek (Hyatt, 1903, p. 58). This zone is widespread.

UNDETERMINED ZONE: The Elk Butte member of the Pierre shale in the lower Missouri Valley is nearly barren, and its equivalents westward have not been determined, except that they must be part of the nonmarine sequence over a large area. No zonal fossil is now suggested.

ZONE OF *Discoscaphites nicolletii* (MORTON): The lower part of the Trail City member of the Fox Hills sandstone is marked by *Discoscaphites nicolletii* (Morton) (1842). It is associated with *D. abyssinus* (Morton) (1842). This zone passes westward into nonmarine

beds that contain the highest occurrence of *Goniobasis? subtortuosa* (Meek and Hayden). This zone is present chiefly in the Great Plains.

ZONE OF *Discoscaphites nebrascensis* (OWEN): The two upper members of the Fox Hills sandstone have not yielded distinctive marine fossils, but the Timber Lake member and the upper part of the Trail City member are marked by *Discoscaphites nebrascensis* (Owen) (1852, p. 577) [= *D. conradi* (Meek, not Morton) (Meek, 1876, p. 430)]. Associated with it are *D. cheyennensis* (Owen) (1852, p. 578), *D. mandanensis* (Morton) (Meek, 1876, p. 443), and a small unnamed *Baculites*, the latest species of the genus in the region. This zone includes the highest part of the ranges of *Sphenodiscus* Meek, "*Belemnitella bulbosa* Meek and Hayden," and *Veniella humilis* (Meek and Hayden). The zone is known only in the Great Plains and passes westward into nonmarine beds.

ZONE OF *Triceratops* MARSH: Dinosaurs of the genus *Triceratops* Marsh (Lull, 1933) are widely reported from the latest Cretaceous deposits, exemplified by the Hell Creek formation, the Lance formation, and the Laramie formation and part of the Denver formation, so much so that it has been common usage to speak of the "*Triceratops* beds" as an inclusive term for the deposits. These nonmarine strata also contain a flora, various reptiles, a few mammals, and such fresh-water mollusks as *Viviparus trochiformis* (Meek and Hayden) (Meek, 1876, p. 580), *Tulotoma thompsoni* White (1883a, p. 100), *Proparreysia holmesiana* (White) (1883a, p. 67), and *P. letsoni* (Whitfield) (1906), and the brackish-water forms *Ostrea glabra* Meek and Hayden and *Brachydontes laticostata* White. These mollusks are useful guides in the Great Plains but range down into lower levels in the more westerly areas where the nonmarine deposits begin earlier.

OTHER ZONES: There are indications of a number of additional zones or subzones, which are either too poorly known or known from too few localities to be included among the zonal indices. Future work may reveal that many of these are good zones of widespread distribution.

In the Frontier formation in central and south-central Wyoming, a form of *Dunveganoceras* is known that differs from *D. pondi* Haas in its flexuous costae. It is associated with a *Metoicoceras* that is closely related to *M. praecox* Haas. Whether this fauna is younger or older than the zone of *D. pondi* remains to be determined.

Recently Haas (1951) described a new ammonite—*Dunveganoceras conditum*—from the Frontier formation of central Wyoming. This form is more closely related to the undescribed species in the zone of *Dunveganoceras* aff. *D. albertense* Warren than to *D. pondi*. In all probability it marks a zone slightly older than the zone of *D.* aff. *D. albertense*.

In Colorado, Utah, and New Mexico, *Scaphites ferronensis* Cobban (1951c, p. 23), an ammonite intermediate between *S. warreni* Meek and Hayden and *S. whitfieldi* Cobban, seems to be confined to the lower part of the *Prionocyclus wyomingensis* zone.

In south-central Wyoming and northwestern Montana a fauna that seems to be post-Sage Breaks and pre-Fort Hays is characterized by small variants of both *Inoceramus deformis* Meek and *I. erectus* Meek. Associated fossils include *Scaphites preventricosus* Cobban, which is more common in the overlying beds containing *Inoceramus deformis*, s. s. However, certain other associated fossils—*Scaphites mariasensis* Cobban (1951c, p. 28) and *Scaphites preventricosus* var. *artilobus* Cobban (1951c, p. 27)—have not been found in the typical *I. deformis* beds. In general the fauna appears more closely related to that of the early Niobrara than to that of the late Carlile.

In the Wind River Basin of Wyoming an undescribed scaphite fauna has been discovered at the top of the Mesaverde formation. The fauna includes *Baculites haresi* Reeside and several common pelecypods that range through rocks equivalent in age to the Eagle sandstone and Claggett shale of Montana. Inasmuch as the scaphites just below the Mesaverde formation belong to the *Scaphites hippocrepis* zone, the new species may be of Claggett age although scaphite species known to be of Claggett age are absent.

Work in progress (January, 1952) indicates that the zone of *Baculites compressus* Say, s. l., can be divided into five subzones. The lowest is marked by *Baculites pseudovatus* Elias (1933, p.

304), the second has as its guide *B. compressus* var. *corrugatus* Elias (1933, p. 303), the third has *Baculites compressus* Say, s.s., the fourth has *B. compressus* var. *reesidei* Elias (1933, p. 302), and the fifth and highest is marked by an unnamed form with stout cross section and smooth venter. Each subzone seems to have, in addition, a diagnostic scaphite.

Broad Faunal Relations

It was long ago determined that the Cretaceous rocks of the Western Interior of the United States are part of the deposits formed in a long, wide belt stretching from eastern Mexico into the Arctic region. In the United States these deposits extend from eastern Arizona, New Mexico, and western Texas northward across the eastern part of the Plateau area, the Rocky Mountain area, and the Great Plains to Montana, North Dakota, and Minnesota. At times a seaway connected the Cretaceous Arctic Ocean and the Cretaceous Gulf of Mexico. The history of this region, as shown by the successive faunas and the lithologic character of the enclosing rocks, is far from simple.

In the Western Interior no assured sedimentary record is known of that part of Early Cretaceous time that corresponds to the Neocomian stage of the European sequence, though the nonmarine Ephraim conglomerate of eastern Idaho and adjacent parts of Wyoming probably represents at least part of it. No pertinent paleontologic evidence is known to the compilers. To the south, in Mexico, marine Neocomian deposits are recognized (Imlay, 1944), and in Canada, on the basis of the flora, Canadian geologists assign the nonmarine Kootenay formation to the Neocomian (Bell, 1946).

The succeeding interval in the Early Cretaceous, corresponding to the Aptian stage of the European sequence, is represented in the Western Interior only by nonmarine deposits in the Peterson-Draney interval above the Ephraim conglomerate of Idaho, by the Cloverly formation of central Wyoming, by the Inyan Kara group of the Black Hills, and by the Kootenai formation of Montana. Deposits of this age are probably lacking over much of the Great Plains. The nonmarine invertebrate fauna is not known to have a close parallel in other parts of the world, and the assignment of the deposits to the Aptian is based entirely on the relationships of the flora to those of other regions (Bell, 1946; Berry, 1929). To the south, in southern Arizona, southern New Mexico, and west Texas, marine deposits of Aptian age are known in the Bisbee group (Stoyanow, 1949) and in the Trinity group (Scott, 1940). To the north, in Canada, the beds assigned to the Aptian are nonmarine. The Gething and McMurray formations in northern British Columbia and Alberta and the lower part of the Blairmore formation in southern British Columbia and Alberta contain a nonmarine fauna and a flora like those of the Kootenai formation of Montana and equivalent deposits (McLearn 1945). Apparently the interior of North America was still the site of only continental deposition during Aptian time; a southern sea invaded only the marginal fringe.

The next higher unit corresponds to the Albian stage of the European sequence and represents the latest part of the Early Cretaceous.

In the Western Interior of the United States, the early part of this interval, the early Albian, may not be represented by sediments. To the south, in southernmost Arizona (Stoyanow, 1949) and in west Texas (Scott, 1940), however, marine deposits in the Bisbee group and in the Trinity group represent the early Albian. To the north, in Canada, marine deposits of this age are found in the lower part of the Fort St. John group (McLearn, 1945) of northern British Columbia and Alberta and nonmarine deposits in part of the Blairmore formation of southern British Columbia and Alberta. The marine faunas north and south are in general unlike, though the ammonite genus *Beudanticeras* is reported in both areas. Probably at this time the boreal waters and the southern waters were still widely separated by areas of continental deposition and erosion.

In mid-Albian time marine waters widely invaded the Western Interior from the south, leaving a record in such units as the Kiowa shale of Kansas, the Purgatoire formation of eastern Colorado and New Mexico, the Skull Creek shale of the Black Hills, and the lower part of the Blackleaf member of the Colorado

shale of Montana. The fauna of these formations is abundant and varied in the south (Twenhofel, 1924) and progressively scarcer and less varied northwestward (Reeside, 1923a). The nonmarine beds of the lower part of the Thermopolis shale of central Wyoming and the nonmarine Bear River formation of southern Wyoming, with its varied fauna (White, 1895), are of this age. To the south, in Texas, the upper part of the marine Fredericksburg group is of this age, and to the north, in Canada, probably part of the marine Fort St. John group (McLearn, 1945) and part of the nonmarine Blairmore formation. Whether the boreal and southern marine waters were connected is not known; if a connection existed, it probably was to the east, in the Swan River formation of Manitoba (Wickenden, 1932) and in some of the beds currently included in the Dakota group of the Great Plains.

Possibly in part contemporaneous with the southern marine invasion, but more likely in later Albian time, volcanic detritus was laid down over a vast area extending from northern Colorado to central Montana and across the entire width of Wyoming (Rubey, 1929). This material, now altered to porcellanite and bentonite, is included in the Mowry and Aspen formations, which are everywhere noted for their content of scales and bones of marine fishes. A few flattened mollusks occur here and there in the volcanic material; however, well-preserved ammonites of the genus *Gastroplites* McLearn have been found at several localities, and of the genus *Neogastroplites* McLearn at other localities (Cobban and Reeside, 1951). These ammonites provide a correlation with the middle and upper parts of the Fort St. John group and indicate strongly that during Albian time a boreal sea extended as far south as northern Colorado and covered Wyoming and Montana. The physical evidence suggests that there was either erosion or nonmarine deposition across central and southern Utah and Colorado and northern Arizona and New Mexico, and the compilers know of no evidence suggesting that this boreal sea reached eastward into much of the Great Plains. To the south, across southern Arizona and New Mexico into Texas, the later deposits of the Comanche series represent an entirely separate southern invasion of this age, with entirely different faunas. In the fauna of this time the only suggestion of a possible connection is the abundant and widespread occurrence of the ammonite genus *Metengonoceras* Hyatt in association with *Gastroplites* and *Neogastroplites*. *Metengonoceras* has been considered to to belong to a group characteristic of the southern faunas. In exposures near the Wyoming-Idaho boundary that may be equivalent to the Aspen formation, nonmarine faunas occur that are in part similar to those of the Bear River formation.

The next higher unit represents the earliest part of the Late Cretaceous and corresponds to the Cenomanian stage. Over much of their area of deposition these beds are marine deposits, though to the west and southwest they become nonmarine or are perhaps absent. The lower part of the Graneros shale in eastern Colorado, the upper part of the Dakota sandstone in western Colorado, and a middle zone of the Frontier formation in east-central Wyoming contain a fauna including the ammonite genus *Calycoceras* Hyatt. This fauna has not been recognized elsewhere in the Western Interior, though the lower part of the Belle Fourche shale is a barren interval that could appropriately contain it. To the south, the Woodbine formation of Texas contains a similar fauna (Stephenson, 1952). In the upper part of the Graneros shale are found a fauna containing *Acanthoceras? amphibolum* Morrow and another with an unnamed species of *Acanthoceras?* These are widely distributed and also have close relatives in the Woodbine formation and in the European Cenomanian. The general trend of evidence is that a wide seaway was open from the south northward possibly across Canada, and in it was deposited the part of the Cenomanian represented by these interior deposits. The succeeding beds with the ammonite genus *Dunveganoceras* seem to have a wide distribution in Canada and southward across Wyoming. The enclosing beds in the Great Plains are the lower members of the Greenhorn formation and their equivalents. The *Dunveganoceras* faunas are not known in the south, but the presence of species of *Metoicoceras* suggests a connection with the Gulf region during this part of the Cenomanian. Possibly the lower part of the Eagle Ford shale (Adkins, 1932, p. 422) would be equiva-

lent to these late Cenomanian deposits, though faunal similarities with the Western Interior are not close. Along the southern and southwestern margins of the Western Interior the first marine deposits seem to be widely of post-Cenomanian age. The immediately preceding nonmarine deposits are mostly sandy and in Arizona, New Mexico, and Utah have commonly been called Dakota sandstone. In western Wyoming they have been included in the lower part of the Frontier formation. A well-characterized nonmarine fauna has not been found in these marginal deposits, unless some of the unnamed beds at the top of the exposures near the Wyoming-Idaho boundary in southwestern Wyoming should prove to be of this age.

The next higher unit, exemplified particularly by the upper members of the Greenhorn formation, corresponds to the lower part of the Turonian stage of the European sequence. It is widespread and is characterized by cosmopolitan faunas that imply nearly free access to the Western Interior from both north and south. In the lower parts *Sciponoceras gracile* (Shumard), *Metoicoceras* Hyatt, and *Inoceramus prefragilis* Stephenson are distinctive. In the upper parts *Inoceramus labiatus* Schlotheim and various other species are distinctive. In Canada a part of the Alberta shale (McLearn, 1937; 1945) is equivalent, and in the Gulf region the middle parts of the Eagle Ford shale contain the lower Turonian faunas (Adkins, 1932, p. 422). This unit is the earliest marine unit over much of the southern and southwestern border of the Western Interior deposits. At some places these beds are missing.

The next unit, exemplified by the Carlile shale, corresponds to the upper part of the Turonian stage of the European sequence. In the Western Interior of the United States it is divisible into a number of faunal units, which, though widely distributed and in part cosmopolitan, have in this region an irregular distribution marked by absence of some units over considerable areas. The middle part of this unit is widely characterized by the presence of sandy deposits, but the lower part is calcareous shale and locally in the Great Plains is a chalk. The ammonites *Collignoniceras* Breistoffer (*Prionotropis* Meek) and *Prionocyclus* Meek and certain of the scaphites identify the divisions of the unit. Their wide distribution in Canada (McLearn, 1937), the Western Interior, and the Gulf region implies free access from both north and south. Parts of the western marginal deposits are nonmarine and locally coal-bearing, but no well-characterized nonmarine fauna has been recorded from them.

The lowest part of the Niobrara formation and equivalents are widely characterized by *Inoceramus deformis* Meek and associated forms, such as the ammonite genus *Barroisiceras* Grossouvre and certain scaphites. The upper part of the Niobrara and equivalents are divisible into faunal units which are recognizable through the central part of the Western Interior into Canada, and which are characterized particularly by a sequence of scaphites. The eastern part of the region shows a chalk facies with a relatively restricted fauna that provides only a general correlation, and in the western marginal part the sequence includes much sandstone and contains nonmarine deposits, particularly toward the south. The upper part of the Niobrara includes the last occurrences of a number of long-ranging species, especially of the pelecypods. In the Gulf region the Austin chalk and its equivalents provide enough identical species to show that these units are undoubtedly the equivalents of the Niobrara formation, but there are striking differences, notably the absence of the abundant scaphites of the Western Interior. These differences strongly suggest a chiefly endemic source for much of the Niobrara fauna, though that fauna could have been in part boreal. There must have been fairly free communication between the Western Interior and the Gulf region, however. Some of the elements of the fauna are cosmopolitan and indicate that the Niobrara formation includes the equivalents of the Coniacian stage of the European sequence and the lower part of the Santonian stage.

The next higher unit, the Telegraph Creek formation and its equivalents, marks the first appearance of a number of species that extend up into much higher levels. This change and the disappearance of older species noted above were observed long ago by Meek and others and were in part the basis for recognizing a major dividing line at the top of the Niobrara formation, between the Colorado and Mon-

tana groups. Though the number of species that cross the boundary is larger than was originally thought, a major break is present. The Telegraph Creek formation is characterized by *Desmoscaphites bassleri* Reeside and certain associated species (Reeside, 1927a). It is widespread west of the Black Hills but is missing along the southwestern margin of the Western Interior and in the Great Plains east of the Black Hills. To the north, in Canada, its presence has been recorded. To the south it is probably represented either by the uppermost part of the Austin chalk or by a hiatus, for little suggestion of its presence is afforded by the published record (Stephenson, 1937). This unit corresponds to the upper part of the Santonian stage. Possibly the Telegraph Creek fauna was largely endemic, and communication with boreal and southern waters was restricted, though the deposits contain cosmopolitan forms, such as the free-floating crinoid *Marsupites*.

The next higher unit, the Eagle sandstone and its equivalents, is marked widely by sandy beds containing *Scaphites hippocrepis* (DeKay) and certain associated species (Reeside, 1927a) Like the Telegraph Creek formation, it is not known in the Great Plains east of the Black Hills and on the southwestern margin of the Western Interior, but is widely distributed west of the Great Plains. To the north, in Canada, there is little record of its presence, but it may represented there. To the south, in the Gulf region, species characteristic of the unit are found in the Taylor marl (Stephenson and Reeside, 1938) and on the Atlantic Coast in the Merchantville clay of New Jersey (Weller, 1907). The suggestion is strong that the Eagle fauna came in from the south. Some of the species of the unit are cosmopolitan and are represented in Europe by identical or closely related forms. The unit corresponds to the lower part of the Campanian stage.

Above the Eagle sandstone and its equivalents are deposits containing a number of faunal units that in the Great Plains constitute the typical Pierre shale. In the Great Plains it is useful to recognize eight lithologic subdivisions, all fine-grained and all marine. Westward, sandstones replace more and more parts of this sequence, and eventually nonmarine deposits make up all of it. In some western marginal areas there are no deposits for much of the interval. In central Montana the Judith River formation and farther west the Two Medicine formation are nonmarine. In central Wyoming, western Colorado, eastern Utah, and northwestern New Mexico the Mesaverde formation is chiefly nonmarine. Along the southwestern margin of the Western Interior, only the latest part of the interval seems to be represented, and the sediments are nonmarine. In the Great Plains a series of faunal zones marks the Pierre shale. Most of these can be traced westward in the marine sandy deposits. The zones are particularly marked by a series of species of *Baculites*, though with each are associated other characteristic species. In general, the faunas are similar to those found to the north, in Canada, and are not matched by closely similar assemblages to the south in part of the Taylor marl and the Navarro group of the Gulf region, (Stephenson, 1941; Stephenson and Reeside, 1938), though enough forms are found to provide a rational correlation. Seemingly the Pierre faunas are either boreal or largely endemic. This aspect is emphasized by the few levels where southern species appear, which indicate a temporarily freer access for these species. These occurrences are all in Colorado, Utah, and southern Wyoming and include such forms as *Trigonia, Exogyra costata* Say, *Capulus spangleri* Henderson, and *Anchura haydeni* White. The relation of these interior faunas to those of Europe is not clear in detail, though there seems no doubt that they correspond to those of the upper Campanian and lower Maestrichtian stages of the European sequence. The nonmarine faunas are not well characterized.

Above the Pierre shale in the Great Plains area lies a sandy formation, the Fox Hills sandstone, divisible into four members in the type area. The two upper members, though marine, have not yielded a satisfactory fauna. The two lower members, however, have yielded faunas in part cosmopolitan, in part apparently endemic. Westward these marine members of the Fox Hills sandstone pass rapidly into overlying nonmarine units, such as the Hell Creek and Lance formations. Sandy marine deposits appear at progressively lower levels westward and have generally been designated

Fox Hills, though many of them contain faunas older than those of the typical Fox Hills sandstone. Some forms, particularly the ammonite *Sphenodiscus* Meek, seem to be associated with the sandstone deposits and appear at lower levels westward than in the typical Fox Hill area. The similarities of the faunas of the Western Interior to those of the Gulf region (Stephenson, 1941; Stephenson and Reeside, 1938) suggest relatively free access to the Western Interior from the Gulf region. Further similarities to European faunas suggest that much of the Fox Hills fauna is cosmopolitan and that there may have been free access across the Arctic regions. The Fox Hills fauna corresponds to the upper Maestrichtian fauna of the European sequence. The nonmarine fauna of the later Cretaecous deposits is well characterized by a number of species.

At the top of the sequence in the Western Interior are widespread nonmarine deposits particularly characterized by a reptilian fauna, of which the genus *Triceratops* Marsh was one of the earliest described and is perhaps the best known. This zone is exemplified by the Hell Creek formation in Montana and the Dakotas, but equivalents under various names are widespread. No equivalent of the "*Triceratops* beds" is recognized in the Gulf region, and outside of North America it may be represented in the marine deposits of the latest Maestrichtian or in the still later Danian stage, if that is Cretaceous.

Above the Hell Creek formation in a small area in North Dakota and South Dakota lie marine deposits, with a considerable fauna of larger invertebrates (Stanton, 1920) and of Foraminifera (Fox, 1942), constituting the Cannonball formation. When first recognized as a separate assemblage, it was noted that there were no ammonites, that some of the mollusks were close to species of the Fox Hills fauna, but that others were close to species of the Paleocene faunas. The formation was assigned to the Cretaceous, because of the Cretaceous-like species and because this seemingly isolated fauna is more readily explained as a relic of the Cretaceous than as a result of a Paleocene invasion. The Foraminifera, however, show very close relations to those of the Paleocene Midway formation of the Gulf region and even closer to those of the Paleocene of northern Europe, and it is now generally agreed that the Cannonball formation is a marine Paleocene unit. Probably the marine waters entered from the Arctic at the close of Hell Creek time. No trace of a connection to the south with the Midway sea has been found, but subsurface extension of the Cannonball formation toward the northwest has been noted, and it seems not unreasonable to postulate a connection farther north.

Annotations

These annotations supplement or explain items in the chart (Pl. 1), and the application of each annotation is indicated by the position of its number *within* one or more columns of the chart.

1. The placement of the boundary between the equivalents of the Campanian and Maestrichtian stages in the Western Interior has long been very uncertain, though most authors have put it at about the base of the zone of *Baculites compressus* Say. The compilers have little basis for judgment in the matter, and the placement shown follows the advice of Dr. J. A. Jeletzky, of the Geological Survey of Canada, who has given special consideration to this problem in western Europe and in Canada. The following statement kindly furnished by Dr. Jeletzky summarizes his hitherto unpublished views on the subject:

> The uncertainty with respect to the Campanian-Maestrichtian boundary in the Western Interior of North America is essentially a reflection of the similar state of affairs in western Europe, where the type-localities of these stages are situated. The writer (1951a, b) has endeavored to settle this uncertainity with regard to western Europe. He feels that it is now possible to recognize at least the approximate position of Campanian-Maestrichtian boundary, as proposed by him for western Europe, in the Western Interior of North America.
>
> Valuable stratigraphical and palaeontological information concerning the younger Upper Cretaceous of the Western Interior of the United States freely given to the writer by Messrs. W. A. Cobban and J. B. Reeside, Jr., has greatly facilitated the conclusions advanced in the following pages.
>
> The Campanian-Maestrichtian boundary in the Western Interior of North America should, in the writer's opinion, be placed provisionally at about the bottom of the zone of *Baculites baculus* Meek and Hayden, subject to the qualification made below. This zone carries in Canada, and apparently in the United States as well, *Scaphites* forms indistinguishable from *Scaphites* (*Hoploscaphites*) *pungens*

Binckhorst, 1861, which in Western Europe (Belgium, Holland) is known only from the rocks of Early Maestrichtian age, where it occurs together with *Scaphites* (*Hoploscaphites*) *constrictus* Sowerby, 1817, and *Pachydiscus neubergicus* Hauer [? = *P. egertoni* (Forbes)]. The uppermost part of the underlying zone of *Baculites compressus* Say carries apparently throughout the Western Interior of North America a densely ribbed ally of *Scaphites* (*Scaphites*) *quadrangularis* Meek which, in the writer's opinion, is indistinguishable from *Scaphites* (*Scaphites*) *elegans* Tate, 1865 (p. 37), from the Antrim Chalk of Northern Ireland. The Antrim Chalk is known to be of latest Campanian age (Jeletzky, 1951b), which agrees well with the assumed earliest Maestrichtian age of the immediately overlying zone of *Baculites baculus* Meek and Hayden, which therefore is here considered as provisionally correlative with the lower part of the Eurasian zone of *Belemnella lanceolata* (Schlotheim), typical form (Jeletzky, 1951a; 1951b).

It should be stressed, however, that there is not nearly enough reliable information about the stratigraphical ranges of the *Scaphites* and *Baculites* forms discussed above to admit of a positive decision on the subject. While it would seem rather unlikely to the present writer that the Campanian-Maestrichtian boundary in the Western Interior of North America could be situated below the zone of *B. baculus*, it appears possible that this latter zone could be of latest Campanian age in part or even totally. Indeed the stratigraphical ranges of *Baculites compressus* Say and of *B. baculus* Meek and Hayden are uncertain for the Canadian part of the Western Interior. At the same time such species of the *B. compressus* zone as *Scaphites* (*Scaphites*) *quadrangularis* Meek, *Scaphites* (*Scaphites*) *brevis* Meek and apparently *Scaphites* (*Scaphites*) *elegans* Tate appear to ascend into the zone of *B. baculus* and to occur there together with *S.* (*S.*) *plenus* Meek and *S.* (*H.*) *pungens* Binckhorst through an uncertain part of this zone. This appears to be true of the middle part of Bearpaw formation in Canada, including the Belanger member, of the upper part of the Lake Creek member of Pierre shale in Kansas (Elias, 1933, p. 292), and of the upper 50 feet of Pierre shale on Cedar Creek (Baker-Glendive anticline) in southeastern Montana (personal communication of W. A. Cobban). Further conflicting evidence is supplied by the first appearance of forms, in the writer's opinion, indistinguishable from *Scaphites* (*Hoploscaphites*) *constrictus* Sowerby somewhat above the beds referable to the zone of *B. baculus* both in Canada and in the United States [e.g. "*Discoscaphites*" *abyssinus* of Elias (Elias, 1933, pl. 39, figs. 3, 6, not figs. 2, 4); "*Discoscaphites*" *abyssinus* of Landes (1940, p. 179–180); and unpublished specimens from the upper Bearpaw in collections of the Geological Survey of Canada]. Also the more or less typical forms of *Scaphites* (*Hoploscaphites*) *nicolletii* Morton, probably partly synonymous with nodate variants of *Scaphites* (*Hoploscaphites*) *tenuistriatus* Kner, seem to make their first appearance in the beds overlying those with *S.* (*S.*) *plenus* Meek and correlative either with the upper part of the *B. baculus* zone or with the overlying zone of *Baculites grandis* Hall and Meek (i.e., upper Bearpaw of Canada; upper part of Mobridge member in Montana, Beecher Island shale member of Kansas, etc.). Both *S.* (*H.*) *constrictus* and *S.* (*H.*) *tenuistriatus* are commonly accepted as index fossils of the Maestrichtian stage, which do not descend even into the uppermost Campanian (zone of *Bostrychoceras polyplocum* Roemer) with the possible exception of a thin transitional bed between these stages. Therefore, one might feet inclined to draw the Campanian-Maestrichtian boundary in the Western Interior of North America at the first appearance of these forms rather than use the other evidence favored by the present writer (occurrence of *S.* (*H.*) *pungens* Binckhorst, and of *S.* (*S.*) *elegans* Tate). This was done especially because the downward extension of the stratigraphical ranges of *S.* (*H.*) *constrictus* and *S.* (*H.*) *nicolletii* into the zone of *B. baculus* and *S.* (*S.*) *plenus* appears to be quite likely, to judge from some fragmentary material in the writer's possession.

A typical specimen of *S.* (*H.*) *nicolletii* Morton, indistinguishable from the one figured by Meek (1876, pl. 34, fig. 2), was collected by the writer in northwestern Germany (Hemmoor), together with *S.* (*H.*) *constrictus* Sowerby, in the upper part of Lower Maestrichtian [zone of *Belemnella lanceolata* (Schlotheim) mut. *sumensis* Jeletzky, 1949]. This gives further support to the above conclusions of the writer and agrees well with the well established fact that, whatever its lowermost occurence might be, the typical *S.*(*H.*) *nicolletii* Morton, as well as the numerous, so far strictly North American, forms of *Scaphites* (*Discoscaphites*) of the group of *conradi* Morton and *Scaphites* (*Discoscaphites*) of the group of *cheyennensis* (Owen) are essentially characteristic of rocks younger than the zone of *B. baculus* and *S.* (*S.*) *plenus*. Whether these latter (i.e., so-called Fox Hill fauna) represent only the higher part of Lower Maestrichtian or embrace some part of Upper Maestrichtian [zones of *Belemnitella junior* Nowak, 1913, and *Belemnella casimirovensis* (Skolozdrowna, 1932, in coll.)] as well is still uncertain. Considering that *Sphenodiscus* spp., which are rather characteristic of the Fox Hills fauna and occur much less commonly in the older Maestrichtian zones of the Western Interior, are essentially characteristic of the Upper Maestrichtian in Europe, it seems by no means unlikely that at least the highest zone with the Fox Hills fauna might be of Late Maestrichtian age.

It may be added in passing that *Belemnitella americana* (Morton, 1829, not Arkhangelsky, 1912) and its Western Interior subspecies *B. bulbosa* Meek, 1876, are rather close allies of the Maestrichtian *Belemnitella junior* Nowak, 1913, and seem to be reliable index fossils of the equivalents of the Maestrichtian stage, at least in the Western Interior of North America. The former species may, however, range into Uppermost Campanian rocks on the Atlantic coast of North America (*e.g.*, New Jersey, Delaware, etc.)

The writer rejects the widely accepted opinion that *Scaphites* of the group of *nodosus* Owen, including *S. plenus* Meek, belong to the subgenus *Acanthoscaphites* Nowak, 1913, which he restricts to the group of *Scaphites* (*Acanthoscaphites*) *tridens* Kner with a median row of tubercles on the ventral side of the living chamber. In his opinion, the group of *S. nodosus* Owen represents immediate Campanian (essentially Upper Campanian) and (?) Lowermost Maestrichtian ancestors of *Scaphites* (*Hoploscaphites*) of the group of *constrictus-nicolletii* and of *Scaphites* (*Discoscaphites*) of the group of *conradi-cheyennensis* as well. There is an uninterrupted series (plexus) of transitional forms between

the three groups above mentioned in the Campanian-Maestrichtian succession of the Western Interior of Canada. *Scaphites* of the group of *nodosus* Owen are placed in the typical subgenus of the genus *Scaphites* Parkinson 1813, s.l., as the writer is unable to see any essential morphological differences between this group and *Scaphites* (*Scaphites*) *binodosus* Roemer, *Scaphites* (*Scaphites*) *hippocrepis* Dekay, *Scaphites roemeri* d'Orbigny and other typical representatives of this subgenus.

1a. Regarding the use of the names *Discoscaphites* and *Acanthoscaphites*, the compilers are in essential agreement with the views expressed in Note 1 by Doctor Jeletzky, but feel that in deference to past usage it would be less confusing, for the purposes of the chart, to continue the old usage until a fully documented and illustrated discussion can be presented.

2. Many authors, particularly the French writers, include the Coniacian and the Maestrichtian stages in the Senonian. Others exclude the Maestrichtian, and others, particularly the German writers, exclude the Coniacian (Emscherian).

3. Col. 1. Nonmarine fossils in the Fort Crittenden formation indicate a very late Cretaceous age for the Sonoita group, which is found in the Santa Rita Mountains (Stoyanow, 1949, p. 58–60).

4. Col. 1. Scant marine fossils suggest a Colorado age for the Amole arkose (Brown, 1939, p. 697).

5. Col. 1. In the Patagonia Mountains (Stoyanow, 1938; 1949, p. 30).

6. Col. 1. In the Ninety-One Hills (Stoyanow, 1938, p. 4–27).

7. Col. 2. Assigned to an early Colorado age on comparison with rocks near Silver City, New Mexico.

8. Cols. 3 and 4. Assigned on the basis of fossils the compilers consider early Colorado.

9. Col. 5, etc. The relations of the sandstone designated "Dakota" in this and many other areas to the typical Dakota sandstone on the Missouri River near Sioux City, Iowa, are not well understood. Such usage of the name may cover beds of both Early and Late Cretaceous ages, though it was apparently the intent originally to include in the Dakota beds no older than the European Cenomanian. There is much doubt that any part of the typical exposures are Late Cretaceous.

10. Col. 7. In Luna County.

11. Col. 7. In the Little Hatchet Mountains.

12. Col. 10. Lee (1906a, p. 240; 1906b, p. 57) reports the presence of *Triceratops*, indicating that at least part of this unit is very late Cretaceous.

13. Col. 10. Paleontologic data indicate the presence of beds of Greenhorn, later Carlile, and Niobrara ages.

14. Col. 10. etc. Presence of beds of early Carlile age here and in several other areas is dubious. The *Collignoniceras woollgari* fauna has not been found, and an interruption in sequence is inferred.

15. Col. 15. Includes the Punta de la Mesa sandstone member of Herrick, as recognized by Lee (Lee and Knowlton, 1917, p. 172, 179).

16. Cols. 16 and 17. On the basis of the dinosaurian faunas, some vertebrate paleontologists assign the interval from the Ojo Alamo sandstone to the Fruitland formation to horizons older than here shown (Gilmore, 1916, 1919).

17. Col. 18. W. T. Lee (1906b, p. 57) at first regarded the Galisteo sandstone as equivalent to the Late Cretaceous deposits of the Engel district (*see* Note 12), because of similarity of lithologic constitution and stratigraphic position, but he later (1917, p. 184) regarded it as Tertiary. Stearns (1943) reports late Eocene or early Oligocene mammals in the uppermost part. The age of the lower part is still undetermined.

18. Col. 26. In the Muddy Mountains.

19. Col. 26. In the Eureka district.

20. Cols. 27 and 28. Paleontological evidence is scant for assignment of these deposits, and they are assigned largely by analogy with deposits to the east.

21. Col. 29, etc. The presence of upper Carlile beds here is dubious. The *Prionocyclus wyomingensis* fauna has not been found, and a hiatus is inferred.

22. Cols. 31, 32, and 38. The lower part of the North Horn formation has yielded Cretaceous reptiles, and the middle part has yielded Paleocene mammals. No sharp boundary between these parts has been noted. Some vertebrate paleontologists assign the reptile-bearing part to horizons older than here shown (Gilmore, 1947). (*See also* Note 16.)

23. Col. 31. The age of the lowest part of the Sanpete formation is not well determined. It may contain beds of Early Cretaceous age.

24. Col. 33. In this area the age of the beds long called "Wasatch" and now designated "Currant Creek" formation is dubious; by analogy with regions to the south they seem likely to be equivalents of the North Horn and Price River formations and at the top may include beds as high as lower Eocene. Adequate paleontologic data are not available.

25. Cols. 34 and 35. Stokes (1944, p. 970) correlates the Kelvin conglomerate with the Buckhorn conglomerate and Cedar Mountain shale (Col. 38). Eardley (1944, p. 838) correlates the type Kelvin conglomerate with the lower part of his Kelvin (?) formation of the Coalville district, Utah (Col. 35), which part appears to be equivalent to the Ephraim formation (Early Cretaceous and possibly Late Jurassic). *See also* Note 42. Adequate paleontologic data are not available.

26. Col. 35. The age of the beds long called "Wasatch" is dubious; it seems likely that they may include equivalents of the Price River and North Horn formations and may extend up into the lower Eocene. Adequate paleontologic data are not available.

27. Col. 35. "Unit W-2," etc., refers to a measured section at Coalville published by Wegemann (1915, p. 163), and "Unit R-1," etc., to a measured section at Rockport published by Stanton (1893, p. 44).

28. Cols. 39 and 43. The relations of the Tuscher formation to the North Horn formation and to the "unnamed sandstone" (Col. 43) are not fully determined. Spieker (1946, p. 140) considers the Tuscher a coarse basal unit of the North Horn formation.

29. Col. 40. The relations of the Mesaverde formation of the Rangely region to that of adjacent areas is not well known. The correlations shown are somewhat arbitrary.

30. Col. 40, etc. The Belle Fourche, Greenhorn, and lower Carlile faunas have not been found here and in several other areas, and a hiatus is inferred.

31. Col. 40, etc. The stratigraphic relations of the strata included in the Dakota sandstone in the areas represented by these columns are not well known. The assignments shown are somewhat arbitrary.

32. Col. 44. The age of the Ohio Creek conglomerate is uncertain, and so is its relation to the "unnamed sandstone" of Col. 43, with which Lee (1912, p. 48) correlated it.

32a. Col. 45. The *Collignoniceras hyatti* and *C. woollgari* zones have not been found here, and an interruption is inferred.

33. Col. 48, etc. No evidence of the Eagle and Telegraph Creek faunas has been found in this or in several other areas, and a hiatus is inferred.

34. Col. 48, etc. Evidence for a disconformity at the base of the Timpas limestone is given by Johnson (1930). In addition, the absence of equivalents of part of the Turner member and of the Sage Breaks member of the Carlile shale may be cited.

34a. Col. 48. The "*Pugnellus* sandstone" of the literature (*see* Stanton, 1893, p. 28) locally occupies the interval between the Codell and Fairport members of the Carlile shale.

35. Col. 48. The Greenhorn and Graneros formations of Gilbert were described in this region (Gilbert, 1896), but, as these names were subsequently applied in the Great Plains to the east, the boundary was moved down to include equivalents of the upper, calcareous part of the original Graneros in the Greenhorn. This revision seems more widely useful.

36. Col. 52. Correlation of the five parts of the Dakota of this region is in dispute. Stanton (1922, p. 266–269) considered all of the Dakota equivalent to the typical Dakota—that is, Late Cretaceous; Reeside (1923a) correlated the marine dark shale with the Glencairn shale, of Kiamichi age; Lee (1927) considered the three lowest parts of the Dakota equivalent to the Cloverly formation of Wyoming and to the Lakota sandstone, Fuson shale, and what is now called the Fall River sandstone of the Black Hills. The compilers believe that Lee's correlation is probably correct, but present evidence is not conclusive.

37. Col. 53, etc. All formations below the level indicated in each column are interpreted from well logs.

38. Col. 54. Correlation of the lower members of the Dakota is arbitrary.

39. Col. 61. The Mentor formation is taken to include all the beds between the Dakota sandstone of common usage and the Permian rocks. Twenhofel (1924, p. 31), who in central Kansas applied the name Mentor to a part of

the interval, adopted the term Belvidere for these strata. For southern Kansas Twenhofel (1924, p. 20) applied the name Belvidere to the beds between the Cheyenne sandstone and the "Dakota" sandstone.

40. Cols. 62, 63, and 65. The Bear River formation of this region has in the lower part fossils related to those of the Cloverly and Kootenai formations and in the upper part fossils more peculiar to the formation—the "Bear River fauna" of the literature. The sandstone called "Tygee" by Mansfield and Roundy (1916, p. 83) and placed by inadvertence at the top of the Gannett group is actually a unit in the Bear River formation. The highest unit of the Gannett group is a discontinuous unnamed red shale (W. W. Rubey, oral communication).

41. Cols. 62 and 63. The Peterson and Draney limestones contain faunas like those of the Kootenai and Cloverly formations.

42. Cols. 62, etc. The Ephraim conglomerate has not yielded significant fossils and is placed arbitrarily. In the lower part it may contain beds of Jurassic age.

42a. Col. 64. The lower part of the typical Adaville formation contains marine fossils of Colorado age. The upper part is not well dated.

43. Col. 64. The lower part of the Beckwith formation has yielded Upper Jurassic fossils; the upper part in this region has not yielded significant fossils and is placed by comparison of lithologic features.

44. Col. 65. In parts of the area the Draney and Peterson limestone are absent.

45. Col. 66. No fossils identifying the equivalents of the Greenhorn and Belle Fourche formations have been reported from this region, and the thickness of beds that could contain them is small. A hiatus is inferred.

46. Col. 67. Post-Bacon Ridge strata are dated only as later Cretaceous. The correlations shown are arbitrary.

47. Col. 67, etc. In much of the literature the name Thermopolis has been applied to dark shales that lie above the Cloverly formation and below the Mowry shale and that contain a brown sandstone member (Muddy). Many geologists now prefer to restrict the name to the lower part of the dark shales, to designate the sandstone the "Muddy sandstone" and view it as a formation, and to include the upper part of the dark shale in the Mowry formation. The compilers think this restricted application of Thermopolis much more useful at many places than the older usage (*see also* Note 52), but in deference to the literature the older usage is shown in the chart.

48. Col. 67. In this region the boundary between the lower member of the Cloverly formation and the Jurassic is in debate. It is not determined whether beds of Morrison age are present or whether all the rocks above the marine Jurassic deposits are part of the early Cretaceous Cloverly formation.

48a. Col. 68. Nomenclature and correlation in this column are largely arbitrary. Paleontologic evidence is scant, and some of the names have been carried far from their original areas.

49. Col. 70. The age of the beds designated "Lewis" and "Lance" is not well known. The assignment shown seems probable but is arbitrary.

50. Col. 70. At many places the Cloverly formation of this region does not present the common threefold sequence. The separation of these beds from the underlying Jurassic is difficult, and at places only arbitrary division is possible.

51. Col. 71. Some authors include this shale and the underlying conglomerate in the Jurassic Morrison formation.

52. Col. 72. The Thermopolis shale, as originally described by Lupton (1916a, p. 168), included the "Rusty beds" usually considered part of the Cloverly formation.

53. Col. 72. The Cloverly formation at its type locality (Darton, 1904) consists chiefly of soft beds and does not show the three divisions—basal conglomerate, middle variegated shale, and upper sandy beds—that at other places led Darton to correlate the formation with the Lakota sandstone, Fuson shale, and Fall River sandstone of the Black Hills. Because the divisions are widely present, they are here indicated.

54. Col. 73. Fossils indicate that the equivalents of much of the Greenhorn formation and lowest part of the Carlile are very thin or missing here, and a hiatus is inferred.

55. Col. 78. The relatively thin sandstone here designated the Cloverly formation may be equivalent to only part of the formation, and

equivalents of the lower parts may have been erroneously included in the Jurassic Morrison formation.

56. Col. 81. The fauna of the Sage Breaks shale was formerly thought to indicate a Niobrara age (Rubey, 1931, p. 4). It is now better known and indicates that the unit is of late Carlile age.

57. Col. 82. Only the Greenhorn limestone is sharply characterized in the log of the Harrisbug well, on which this section is largely based.

58. Col. 83. The Pierre, Niobrara, and Carlile formations are not distinguishable in the log of the Agate well, on which this section is based.

59. Col. 86. The age of the lower part of the Dakota here is not determined.

60. Col. 87. The compilers believe that the marine fauna of the type Dakota sandstone—Omadi sandstone of Condra and Reed (1943)—is part of the general assemblage of marine organisms represented in the Kiowa shale, Mentor formation, and the Purgatoire formation and therefore of about Kiamichi (late Early Cretaceous) age. No evidence of the presence in the type Dakota of equivalents of the Lakota sandstone and Fuson shale is known to the compilers. The age of the lower part of the Graneros shale here is not determined.

61. Col. 90. This was previously called "Middle Creek limestone member" by Wing (1940) and "Bull Creek limestone" by Moore (1949). In a diagram for this region, Moore has used, within the the Greenhorn formation the names "Willow Creek," "Stoneville Flats," and "Crow Creek" for limestone members.

62. Col. 94. The Carlile and Greenhorn formations are reported to contain distinctive fossils, but the age of the Graneros shale is not well determined. Possibly the Dakota sandstone contains no Late Cretaceous deposits.

63. Col. 97. The relations of these beds to the coal-bearing rocks called the Frontier formation in central eastern Idaho (Col. 63) is not known, though they may be equivalent.

64. Col. 100. Very little evidence is available as to the age of these volcanic rocks.

65. Col. 100. Sediments representing the time of the Belle Fourche, Greenhorn, and Carlile formations and the lower part of the Niobrara formation are thin or missing in the central part of Jefferson County (M. R. Klepper, unpublished data). Farther north these strata are present.

66. Col. 102. The limits of the typical Blackleaf sandy member of Stebinger (1918, p. 158) are as shown, but petroleum geologists, for convenience in subsurface studies, carry the name up to include the calcareous member.

66a. Col. 102. The names Cosmos and Vanalta are applied to sands that are local equivalents of the Cut Bank sandstone (Erdmann and Schwabraw, 1941). The names Lander and Moulton are applied to local sands in the Kootenai formation (Blixt, 1941).

67. Col. 104 and 105. The relations of the sandstones in the lower part of the Colorado shale and in the upper part of the Kootenai formation are not determined. Probably equivalents of the Muddy sandstone and of the Greybull sandstone of Wyoming are widely present, and the intervening shales are to be correlated with parts of the Thermopolis shale of Wyoming.

68. Col. 128. The age of the Windrow formation is conjectural. Stauffer and Thiel (1941, p. 102) note that the upper part resembles the Ostrander member of the Dakota formation and that the lower part is of residual material that may be much older than Cretaceous.

Index by Columns of Stratigraphic Names

Numbers refer to numbered columns in Plate 1. Where one column only is cited, it contains the type occurrence of the name; where two or more columns are cited, an asterisk (*) indicates the column containing the type occurrence.

The following units have type occurrences in Canada: Ashville, Assiniboine, Boissevain, Boyne, Keld, Kootenai, Morden, Odanah, Pembina, Riding Mountain, St. Mary River, Swan River, and Vermilion River.

Aberdeen 38
Adaville 64
Adel Mountain 100
Agency 87, 92*
Allen Valley 31
Allison 14,* 17
Almond 69
Amole 1
Anchor Mine 43
Animas 19, 41*
Apishapa 20, 21, 48,* 49, 52, 79
Arapahoe 52
Ardmore 89

Ashville 116
Aspen 33, 35, 40, 46, 63, 64,* 66
Asphalt Ridge 40
Assiniboine 116
Atarque 6
Bacon Ridge 67
Bartlett 14
Baxter 69
Bearpaw 78, 102, 103, 104, 105, 106,* 107, 108, 109, 111
Bear River 35, 62, 63, 64,* 66
Beartooth 9
Beaver Creek 81
Bechler 62,* 63, 65
Beckwith 64
Beecher Island 54,* 57
Belle Fourche 78, 80, 81,* 83, 89, 90, 103, 110
Bell Mountain 11
Belvidere 61 (Note 39)
Benton 21, 50, 51, 53, 54, 57, 76, 79, 106,* 112, 113, 115, 117, 118, 123
Big Cottonwood 120
Big Elk 105
Birdhead 103
Bisbee 1,* 7
Blackhawk 38,* 39
Blackleaf 102
Blair 69
Bluecastle 39
Blue Gate 36
Blue Hill 55, 59*
Boissevain 116
Bowie 44
Boyne 116
Breien 113
Bridge Creek 48, 55*
Broken Jug 7
Buck 39
Buckhorn 38
Buda 8
Bull Creek 90 (Note 6)
Burro Canyon 42,* 43
Carlile 19, 20, 21, 48,* 49, 52, 55, 59, 60, 68, 73, 74, 77, 78, 80, 81, 82, 83, 84, 85, 86, 87, 89, 90, 91, 92, 93, 94, 103, 110, 114
Castlegate 38,* 39
Cat Creek 105, 106, 107, 108,*
Cedar Mountain 38
Chacra 17
Chamiso 11
Cheyenne 24, 56, 58,* 59
Cholla 1
Cintura 1
Claggett 68, 102, 103, 104, 105, 106,* 107, 108, 109, 111
Cliff House 16, 41*
Cloverly 67, 68, 70, 71, 72,* 73, 74, 75, 76, 77, 78, 79, 103
Coalmont 51
Cockrum 56
Codell 48, 49, 52, 53, 55, 59,* 79, 80
Cody 67, 70, 71,* 72, 78, 103
Coleraine 127
Colgate 110
Colorado 7, 8, 9, 49,* 52, 78, 97, 98, 99, 100, 101, 102, 104, 105, 106, 107, 108, 109, 110, 111
Corbett 7
Cosmos 102 (Note 66)
Crow Creek 87, 92*
Crow Creek (2d) 90 (Note 61)
Currant Creek 33
Cut Bank 102
Dakota 5, 6, 8, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 24, 29, 30, 33, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 57, 59, 61, 69, 84, 85, 86, 87,* 88, 91, 92, 93, 94, 95, 96, 99, 112, 113, 114, 115, 118, 119, 121, 122, 124, 125, 126
Dalton 15
Dawson 49
DeGrey 87, 91, 92*
Del Rio 8
Denver 52
Dilco 11, 14,* 15
Draney 62,* 63, 65, 66
Eagle 68, 100, 102, 103, 104, 105, 106,* 107, 108, 109, 110, 111
Eagle Ford 8
Edwards 8
Elk Basin 103
Elk Butte 87, 92*
Emery 36, 38,*
Ephraim 35, 62,* 64, 65, 66
Ericson 69
Fairport 48, 49, 52, 55, 59*
Fall River 60, 80, 81, 84, 89,* 90, 110
Farmington 16,* 41
Farrer 39
Favel 116
Ferris 74
Ferron 36, 38*
Finlay 8
Fort Benton 106
Fort Buchanan 1
Fort Crittenden 1
Fort Hays 48, 53, 54, 55, 57, 59,* 84
Fox Hills 49, 50, 52, 53, 79, 80, 81, 82, 90, 91, 92,* 110, 111, 112, 113, 114
Frontier 33, 35, 40, 63, 64,* 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 103
Fruitland 16,* 17, 19, 41
Funk Valley 31
Fuson 60, 80, 81, 84, 85, 89,* 90, 110
Galisteo 18
Gallego 11
Gallup 6, 11, 14,* 15
Gammon 81,* 90, 110
Gannett 35, 62,* 63, 64, 65, 66
Garley Canyon 38
Gastropod 97, 100
Georgetown 8
Gibson 11, 14,* 15, 17, 19
Glance 1
Glencairn 48,* 49
Graneros 19, 20, 21, 22, 24, 48,* 49, 52, 55, 59, 60, 80, 81, 82, 83, 84, 85, 86, 87, 89, 90, 91, 92, 93, 94, 110, 114, 122, 124
Greenhorn 19, 20, 21, 24, 48,* 49, 52, 55, 59, 60, 78, 80, 81, 82, 83, 84, 85, 86, 87, 89, 90, 91, 92, 93, 94, 103, 110, 114
Gregory 87, 91, 92*
Greybull 68, 71, 72,* 103
Groat 81
Hartland 48, 55, 59*
Haybro 47
Hayden Gulch 47
Hell Creek 82, 90, 92, 103, 104, 105, 106, 107, 108, 109, 110, 111,* 112, 113, 114
Henefer 35
Hidalgo 7
Hilliard 64
Holderness 47

Horsehead 6
Horsethief 102
Hosta 11, 15,* 17, 19
Howells Ridge 7
Hunter Canyon 43
Hygiene 52
Ies 45, 46, 47*
Indianola 31, 32*
Interior 87, 91*
Inyan Kara 80, 81,* 89, 90, 110
Iron Springs 28
Janssen 59
Jetmore 59
Joserita 1
Juana Lopex 16, 17, 18,* 19
Judith River 68, 102, 104, 105, 106,* 107, 108, 109, 110, 111
Kaiparowits 29, 30*
Keld 116
Kelvin 34,* 35
Kemmerer 64
Kiamichi 8
Kiowa 24, 56, 58,* 59
Kirtland 16,* 17, 19, 41
Kootenai 97, 98, 99, 100, 101, 102, 104, 105, 106, 107, 108, 109, 111
Lake Creek 57
Lakota 60, 80, 81, 84, 85, 89, 90,* 110
Lance 47, 69, 70, 71, 72, 73, 77, 78, 79, 80,* 81
Lander 102 (Note 66)
Laramie 49, 50, 52,* 53, 99
Larimer 52
La Ventana 17,* 19
Lazeart 64
Lennep 104, 105*
Lewis 16, 17, 19, 41,* 47, 69, 70, 73, 74, 75, 77
Lincoln 48, 55, 59*
Lion Canyon 45
Livingston 99, 101*
Lowell 1
Lytle 48,* 49
McDermott 16, 41*
Mancos 5, 6, 11, 12, 14, 15, 16, 17, 18, 19, 33, 36, 37, 38, 39, 40, 41,* 42, 43, 44, 45, 46, 47
Masuk 36
Medicine Bow 74
Meeteetse 71,* 72
Menefee 16, 41*
Mentor 61
Mesa Rica 22
Mesaverde 5, 6, 11, 12, 14, 15, 16, 17, 18, 19, 33, 36, 38, 39, 40, 41,* 42, 43, 44, 45, 46, 47, 67, 69, 70, 71, 72, 73, 74, 75, 76, 77
Middle Creek 90 (Note 61)
Middle Park 51
Miguel 11
Milliken 52
Milner 47
Minnewaste 89
Mitten 81
Mobridge 87, 91, 92*
Molly Gibson 1
Montana 99, 106*
Monument Hill 81
Morapos 47
Morden 116
Morita 1
Mosby 108,* 109
Moulton 102 (Note 66)
Mount Garfield 43
Mount Harris 47
Mowry 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78,* 79, 80, 81, 83, 89, 90, 103, 104, 106, 108, 109, 110, 111
Muddy 67, 70, 71, 72,* 73, 75, 76, 77, 108, 109
Mulatto 15
Mural 1
Nefsy 81
Neslen 39
Newcastle 60, 78, 80, 81,* 83, 84, 89, 90, 110
Niobrara 19, 21, 48, 49, 50, 51, 52, 53, 54, 55, 57, 59, 60, 68, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87,* 89, 90, 91, 92, 93, 103, 110, 112, 113, 114, 115
North Horn 31, 32, 38*
Oacoma 87, 92*
Odanah 116
Ohio Creek 44
Ojo Alamo 16,* 17
Omadi 84, 86, 87,* 88
Orman Lake 90
Ostrander 121
Overton 26
Oyster Ridge 35, 64*
Pacheta 1
Pajarito 22
Panther 38
Paonia 44
Parkman 68, 77, 78,* 103
Patagonia 1
Peay 72
Pedregosa 1
Pedro 81
Pembina 116
Perilla 1
Pescado 6,* 11
Peterson 62,* 63, 65, 66
Pfeifer 59
Pictured Cliffs 16,* 17, 19, 41
Pierre 20, 21, 48, 49, 50, 51, 52, 53, 54, 57, 78, 79, 80, 81, 82, 83, 86, 87, 89, 90, 91, 92,* 93, 110, 112, 113, 114, 115, 117
Pine Ridge 75
Piney 78
Pinkard 3
Pinto 28
Playas Peak 7
Point Lookout 16, 41*
Price River 31, 32, 38*
Pryor 68, 103*
Pugnellus 48 (Note 43a)
Punta de la Mesa 15 (Note 15)
Purgatoire 20, 21, 22, 24, 48,* 49, 55, 57
Quajote 1
Rail Canyon 21
Raton 21,* 48
Recreation 1
Red Speck 102
Richards 52
Riding Mountain 116
Rim Rock 40,* 45
Ringbone 7
Rock Springs 69
Rocktown 59
Rocky Ridge 52
Rollins 44
Rusty 67, 70
Saavedra 1
Sage Breaks 75, 76, 80, 81,* 89, 90
Sage Hen 108
St. Mary River 102
Salt Grass 57

Sanpete 31
Sarten 7
Satan 11, 15*
Sego 39,* 43
Shannon 77,* 78, 80
Sharon Springs 48, 52, 57,* 87, 89, 90, 91, 92
Shoshone 50
Sixmile Canyon 31
Skull Creek 78, 80, 81,* 83, 84, 89, 90, 110
Skunk Ranch 7
Smoky Hill 48, 53, 54, 55, 57, 59,* 84
Sonoita 1
Spring Canyon 38
Star Point 38
Steele 73,* 74, 75, 76, 77, 78
Stoneville Flats 90, (Note 61)
Storrs 38
Straight Cliffs 29, 30*
Sully 87, 92*
Sulphur Canyon 39
Sunburst 102
Sussex 78
Swan River 116
Tancredia 106
Teapot 73, 77*
Telegraph Creek 68, 100, 101, 102, 103*
Tepee Buttes 48, 49, 53
Terra Cotta 59
Terry 52
Thatcher 48
Thermopolis 67, 68, 69, 70, 71, 72,* 73, 74, 75, 76, 77, 78, 103, 109
Thompson Canyon 39
Timber Lake 92
Timpas 20, 21, 48, 49,* 52, 79
Tocito 16
Torchlight 72
Torrington 79
Trail City 92
Tres Hermanos 11, 15,* 18
Trinidad 21, 48*
Tropic 29, 30*
Trout Creek 40, 45, 47*
Tucumcari 22
Tununk 36
Turner 81,* 89, 90
Tuscher 39
Twentymile 47
Two Medicine 100, 101, 102*
Twowells 6
Tygee 62
Vanalta 102 (Note 66)
Verendrye 87, 91, 92*
Vermejo 21,* 48
Vermilion River 116
Virgelle 68, 100, 101, 102, 103, 104, 105, 106,* 108, 109
Virgin Creek 87, 91, 92*
Wahweap 29, 30*
Wall Creek 73, 74, 75, 76, 77,* 80
Warm Creek 109
Wasatch 35
Wayan 62
Weskan 57
Williams Fork 40, 45, 46, 47*
Willow Creek 90 (Note 61)
Windrow 128
Woodbine 8

References

1. Adkins, W. S. (1928) *Handbook of Texas Cretaceous fossils*, Univ. Texas, Bull. 2838, 385 pages.
2. —— (1931) *Some Upper Cretaceous ammonites in western Texas*, Univ. Texas, Bull. 3101, p. 35–72, Pl. 2–5.
3. —— (1932) *The Mesozoic systems in Texas*, in *The geology of Texas, vol. 1*, Univ. Texas, Bull. 3232, p. 239–518.
4. Allison, I. A. (1932) *The geology and water resources of northwestern Minnesota*, Minn. Geol. Survey, Bull. 22, p. 60, 188, 231.
5. Andrews, D. A. (1944) *The Willow Creek coal area, near Kemmerer, Wyoming*, U. S. Geol. Survey, Coal Prelim. Map.
6. Arkell, W. J. (1947) *The geology of Oxford*, 128 pages, Oxford.
7. Bain, H. F. (1895) *Cretaceous deposits of the Sioux Valley*, Iowa Geol. Survey, Rept., vol. 3, p. 101–114.
8. Baker, A. A. (1933) *Geology and oil possibilities of the Moab district, Grand and San Juan counties, Utah*, U. S. Geol. Survey, Bull. 841, p. 54–56.
9. ——; Dane, C. H.; and Reeside, J. B., Jr. (1936) *Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado*, U. S. Geol. Survey, Prof. Paper 183, p. 58–63.
10. Barnett, V. H. (1916) *Geology of the Hound Creek district of the Great Falls coal field, Cascade County, Montana*, U. S. Geol. Survey, Bull. 641, p. 222–223.
11. Barry, J. G., and Melsted, V. J. (1908) *The geology of northeastern North Dakota, with special reference to cement materials*, N. D. State Geol. Survey, 5th Bienn. Rept., p. 150–184.
12. Bass, N. W. (1926a) *Geologic investigations in western Kansas: part 1, Geology of Ellis County*, Kans. Geol. Survey, Bull. 11, p. 15, 19–37.
13. —— (1926b) *Geologic investigations in western Kansas: part 2, Geology of Hamilton County*, Kans. Geol. Survey, Bull. 11, p. 59, 61–76.
14. —— (1946) *Subsurface maps of the Rangely anticline, Rio Blanco County, Colorado*, U. S. Geol. Survey, Oil and Gas Invest., Prelim. Map 67.
15. ——; Straub, C. E.; and Woodbury, H. O. (1947) *Structure contour map of the surface rocks of the Model anticline, Las Animas County, Colorado*, U. S. Geol. Survey, Oil and Gas Invest., Prelim. Map 68.
16. Bauer, C. M. (1924) *The Ekalaka lignite field, southeastern Montana*, U. S. Geol. Survey, Bull. 751, p. 236–243.
17. Beck, Elfred (1929) *Salt Creek oil field, Natrona County, Wyoming*, Structure of typical American oil fields, vol. 2, p. 591–597.
18. Beekly, A. L. (1912) *The Culbertson lignite field, Valley County, Montana*, U. S. Geol. Survey, Bull. 471, p. 319–358.
19. —— (1915) *Geology and coal resources of North Park, Colorado*, U. S. Geol. Survey, Bull. 596, p. 20, 30–66.
20. Bell, W. A. (1946) *Age of the Canadian Koot-*

nay formation, Am. Jour. Sci., vol. 244, no. 7, p. 513–526.

21. Bergquist, H. R. (1944) *Cretaceous of the Mesabi Range, Minnesota*, Jour. Paleont., vol. 18, p. 8.
22. Berkey, C. P. (1905) *Economic geology of the Pembina region of North Dakota*, Am. Geol., vol. 35, p. 142–152.
23. Berry, E. W. (1929) *The Kootenay and Lower Blairmore floras*, in *Mesozoic paleontology of the Blairmore region*, Nat. Mus. Canada, Bull. 58, p. 28–54.
24. Berry, G. W. (1943) *Stratigraphy and structure at Three Forks, Montana*, Geol. Soc. Am., Bull., vol. 54, p. 20–22.
25. Blixt, J. E. (1941) *Cut Bank oil and gas field, Glacier County, Montana*, Am. Assoc. Petrol. Geol., Stratigraphic Type Oil Fields, p. 327–362.
26. Boese, Emil (1906) *Excursion au Cerro de Muleros*, 10th Inter. Geol. Cong., Mexico, Guide to Excursion 20.
27. —— (1910) *Monografía geológica y paleontológica del Cerro de Muleros*, Inst. geol. México, Bol. 25, p. 16–18, 28–30.
28. Bowen, C. F. (1919) *Anticlines in a part of the Musselshell Valley, Musselshell, Meagher, and Sweetgrass counties, Montana*, U. S. Geol. Survey, Bull. 691, p. 188–197.
29. Branson, E. B., and Branson, C. C. (1941) *Geology of the Wind River Mountains, Wyoming*, Am. Assoc. Petrol. Geol., Bull., vol. 25, p. 120–151.
30. Brown, W. H. (1939) *Tucson Mountain, an Arizona Basin Range type*, Geol. Soc. Am., Bull., vol. 50, p. 697–760.
31. Bullard, F. M. (1928) *Lower Cretaceous of western Oklahoma; a study of the outlying areas of the Lower Cretaceous in Oklahoma and adjacent States*, Okla. Geol. Survey, Bull. 47, 116 pages.
32. Calvert, W. R. (1912) *The Livingston and Trail Creek coal fields, Park, Gallatin, and Sweetgrass counties, Montana*, U. S. Geol. Survey, Bull. 471, p. 386–390.
33. Campbell, M. R. (1904) *The Deer Creek coal field, Arizona*, U. S. Geol. Survey, Bull. 225, p. 240–258.
34. —— in Wilmarth, M. G. (1931) *Correlation of named geologic units of Colorado*, U. S. Geol. Survey, chart, col. 1.
35. Clark, F. R. (1928) *Economic geology of the Castlegate, Sunnyside, and Wellington quadrangles, Carbon County, Utah*, U. S. Geol. Survey, Bull. 793, p. 10–20.
36. Cobban, W. A. (1951a) *Colorado shale of central and northwestern Montana and equivalent rocks of Black Hills*, Am. Assoc. Petrol. Geol., Bull. vol. 35, p. 2170–2198.
37. —— (1951b) *New species of* Baculites *from the Cretaceous of Montana and South Dakota*, Jour. Paleont., vol. 25, p. 817–821.
38. —— (1951c [1952]) *Scaphitoid cephalopods of the Colorado group*, U. S. Geol. Survey, Prof. Paper 239, 42 pages.
39. ——; Patterson, S. H.; Richards, P. W.; and others (1949) *Section of rocks exposed in Bighorn River Canyon-Hardin area, Big Horn County, Montana*, Wyo. Geol. Assoc., Guidebook 4th Ann. Field Conf. in Powder River Basin, chart in pocket.
40. —— and Reeside, J. B., Jr. (1951) *Occurrence of Lower Cretaceous ammonites in Colorado, Wyoming, and Montana*, Am. Assoc. Petrol. Geol., Bull., vol. 35, p. 1892–1893.
41. Collier, A. J. (1920) *Anticlines near Maverick Springs, Fremont County, Wyoming*, U. S. Geol. Survey, Bull. 711, p. 158–160.
42. —— (1924) *The Scobey lignite field, Valley, Daniels, and Sheridan Counties, Montana*, U. S. Geol. Survey, Bull. 751, p. 164–166.
43. —— (1930) *The Kevin-Sunburst oil field and other possibilities of oil and gas in the Sweetgrass arch, Montana*, U. S. Geol. Survey, Bull. 812, p. 61, 69–75.
44. —— and Cathcart, S. H. (1922) *Possibility of finding oil in laccolithic domes south of the Little Rocky Mountains, Montana*, U. S. Geol. Survey, Bull. 736, p. 171–178.
45. Collignon, Maurice (1931) *Faunes sénoniennes du nord et de l'ouest de Madagascar*, Service géol. Mines Madagascar, Ann. géol., fasc. 1.
46. Condra, G. E. (1908) *Geology and water resources of a portion of the Missouri River Valley in northeastern Nebraska*, U. S. Geol. Survey, W.-S. Paper 215, p. 8–17.
47. —— and Reed, E. C. (1943) *The geological section of Nebraska*, Nebr. Geol. Survey, Bull. 14, p. 14–20, Fig. 7.
48. ——; Schramm, E. F.; and Lugn, A. L. (1931) *Deep wells of Nebraska*, Nebr. Geol. Survey, ser. 2, Bull. 4, p. 8–17, 39–43, 175–177, 224, 245–247, 251–257, 265–267.
49. Conrad, T. A. (1875) *in* Cope, E. D.: *The Vertebrata of the Cretaceous formations of the West*, U. S. Geol. Geog. Survey Terr., Rept., vol. 2, p. 23, 24.
50. Crandell, D. R. (1950) *Revision of Pierre shale of central South Dakota*, Am. Assoc. Petrol. Geol., Bull., vol. 34, p. 2337–2346.
51. Cross, Whitman (1907) *Ouray quadrangle, Colorado*, U. S. Geol. Survey, Geol. Atlas, Folio 153.
52. Crowley, A. J. (1951) *Possible Lower Cretaceous uplifting of Black Hills, Wyoming and South Dakota*, Am. Assoc. Petrol. Geol., Bull., vol. 35, p. 83–90.
53. Dane, C. H. (1936) *Geology and fuel resources of the southern part of the San Juan Basin, New Mexico; part 3, The La Ventana-Chacra Mesa coal field*, U. S. Geol. Survey, Bull. 860–C, p. 91–121, Pl. 41.
54. —— (1946) *Stratigraphic relations of Eocene, Paleocene, and latest Cretaceous formations of eastern side of San Juan Basin, New Mexico*, U. S. Geol. Survey, Oil and Gas Invest., Prelim. Chart 24.
55. ——; Pierce, W. G.; and Reeside, J. B., Jr. (1937) *The stratigraphy of the Upper Cretaceous rocks north of the Arkansas River in eastern Colorado*, U. S. Geol. Survey, Prof. Paper 186, p. 209–232.
56. Darton, N. H. (1902) *Oelrichs quadrangle, South Dakota*, U. S. Geol. Survey, Geol. Atlas, Folio 85.
57. —— (1904) *Comparison of the stratigraphy of the Black Hills, Bighorn Mountains, and Rocky Mountain Front Range*, Geol. Soc. Am., Bull., vol. 15, p. 394–401.

58. Darton, N. H. (1905) *Preliminary report of the geology and underground water resources of the central Great Plains*, U. S. Geol. Survey, Prof. Paper 32, p. 214.
59. —— (1906) *Cloud Peak-Fork McKinney quadrangles, Wyoming*, U. S. Geol. Survey, Geol. Atlas, Folio 142.
60. —— (1909a) *Geology and underground waters of South Dakota*, U. S. Geol. Survey, W.-S. Paper 227, p. 52.
61. —— (1909b) *Belle Fourche quadrangle, South Dakota*, U. S. Geol. Survey, Geol. Atlas, Folio 164.
62. —— (1916) *Geology and underground water of Luna County, New Mexico*, U. S. Geol. Survey, Bull. 618, p. 43–45.
63. —— (1919) *Newell quadrangle, South Dakota*, U. S. Geol. Survey, Geol. Atlas, Folio 209.
64. —— (1925) *A résumé of Arizona geology*, Univ. Ariz., Bull. 119, p. 146, 150, 205.
65. —— (1928) *"Red beds" and associated formations in New Mexico*, U. S. Geol. Survey, Bull. 794, p. 43, 74–76, 271.
66. —— and Paige, Sidney (1925) *Central Black Hills, South Dakota*, U. S. Geol. Survey, Geol. Atlas, Folio 219.
67. —— — Siebenthal, C. E. (1909) *Geology and mineral resources of the Laramie Basin, Wyoming*, U. S. Geol. Survey, Bull. 364, p. 30–37.
68. —— — Smith, W. S. T. (1904) *Edgemont quadrangle, South Dakota*, U. S. Geol. Survey, Geol. Atlas, Folio 108.
69. ——; Blackwelder, Eliot; and Siebenthal, C. E. (1910) *Laramie-Sherman quadrangles, Wyoming*, U. S. Geol. Survey, Geol. Atlas, Folio 173.
70. Dobbin, C. E. (1930) *The Forsyth coal field, Rosebud, Treasure, and Big Horn counties, Montana*, U. S. Geol. Survey, Bull. 812, p. 8–14.
71. —— (1939) *Geological structure of St. George district, Washington County, Utah*, Am. Assoc. Petrol. Geol., Bull., vol. 23, p. 121–144.
72. —— and Horn, G. H. (1949) *Geology of the Mush Creek and Osage oil fields and vicinity, Weston County, Wyoming*, U. S. Geol. Survey Oil and Gas Invest., Prelim. Map 103.
73. —— — Larsen, R. M. (1934) *Geologic and structure contour map of the southern half of the Cedar Creek anticline, Fallon County, Montana, and Bowman County, North Dakota*, U. S. Geol. Survey.
74. ——; Bowen, C. F.; and Hoots, H. W. (1929) *Geology and coal and oil resources of the Hanna and Carbon Basins, Carbon County, Wyoming*, U. S. Geol. Survey, Bull. 804, p. 9–25, pls. 8, 10, 26.
75. ——; Hoots, H. W.; and Dane, C. H. (1928) *Geology and oil and gas possibilities of the Bell Springs district, Carbon County, Wyoming*, U. S. Geol. Survey, Bull. 796, p. 174, 181–185, Pl. 26.
76. ——; ——; ——; and Hancock, E. T. (1929) *Geology of the Rock Creek oil field and adjacent areas, Carbon and Albany counties, Wyoming*, U. S. Geol. Survey, Bull. 806, p. 134, 138–142, Pl. 42.
77. Dobrovolny, Ernest (1940) *Jurassic and Cretaceous strata of the Camp Davis area, Wyoming*, Mich. Acad. Sci. Arts Letters, Papers, vol. 26, p. 429–443.
78. ——; Summerson, C. H.; and Bates, R. L. (1947) *Geology of northwestern Quay County, New Mexico*, U. S. Geol. Survey, Oil and Gas Invest., Prelim. Map 62.
79. Dorf, Erling (1942) *Flora of the Lance formation at its type locality*, Carnegie Inst. Washington, Pub. 508, p. 88–92.
80. Dunbar, C. O., and others (1942) *Correlation charts prepared by the Committee on Stratigraphy of the National Research Council*, Geol. Soc. Am., Bull., vol. 53, p. 429–434.
81. Eardley, A. J. (1944) *Geology of the central Wasatch Mountains, Utah*, Geol. Soc. Am., Bull., vol. 55, p. 838–842.
82. Ehlers, Allen (1943) *Williston Basin wildcat test, Oliver County, North Dakota*, Am. Assoc. Petrol. Geol., Bull., vol. 27, p. 1618–1622.
83. Eldridge, G. H. (1888) *On some stratigraphical and structural features of the country about Denver, Colorado*, Colo. Sci. Soc., Pr., vol. 3, footnote on p. 3.
84. —— (1894) *Description of the sedimentary formations, Anthracite-Crested Butte quadrangles, Colorado*, U. S. Geol. Survey, Geol. Atlas, Folio 9, p. 6–7.
85. Elias, M. K. (1931) *The geology of Wallace County, Kansas*, Kans. State Geol. Survey, Bull. 18, p. 28–131.
86. —— (1933) *Cephalopods of the Pierre formation of Wallace County, Kansas, and adjacent area*, Univ. Kans., Bull., vol. 34, no. 5, p. 289–363.
87. Emery, W. B. (1929) *Lance Creek oil and gas field, Niobrara County, Wyoming*, Am. Assoc. Petrol. Geol., Structure of typical American oil fields, vol. 2, p. 605.
88. Emmons, W. H., and Calkins, F. C. (1913) *Geology and ore deposits of the Philipsburg quadrangle, Montana*, U. S. Geol. Survey, Prof. Paper 78, p. 33.
89. Erdmann, C. E. (1930) *Preliminary structure contour map of the Bears Den-Flat Coulee-Whitlash districts, north-central Montana*, U. S. Geol. Survey.
90. —— (1934) *The Book Cliffs coal field in Garfield and Mesa counties, Colorado*, U. S. Geol. Survey, Bull. 851, p. 22, 23, 27–55, Pls. 4, 5.
91. —— and Larsen, R. M. (1934) *Geologic and structure contour map of the northern half of the Cedar Creek anticline, Dawson, Prairie, Wibaux, and Fallon Counties, Montana*, U. S. Geol. Survey.
92. —— — Schwabrow, J. R. (1941) *Border-Red Coulee oil field, Toole County, Montana, and Alberta, Canada*, Am. Assoc. Petrol. Geol., Stratigraphic Type Oil Fields, p. 274–301.
93. ——; Beer, William; and Nordquist, J. W. (1946) *Preliminary structure contour map of the Cut Bank-West Kevin-Border districts, Glacier, Toole, and Pondera counties, Montana (Revised)*, U. S. Geol. Survey.
94. Fath, A. E., and Moulton, G. F. (1924) *Oil and gas fields of the Lost Soldier-Ferris district, Wyoming*, U. S. Geol. Survey, Bull. 756, p. 10, 11, 17–28.
95. Finlay, G. I. (1916) *Colorado Springs quad-*

rangle, Colorado, U. S. Geol. Survey, Geol. Atlas, Folio 203.

96. Fisher, C. A. (1909) *Geology of the Great Falls coal field, Montana*, U. S. Geol. Survey, Bull. 356, p. 36–38.
97. Fisher, D. J. (1936) *The Book Cliffs coal field in Emery and Grand Counties, Utah*, U. S. Geol. Survey, Bull. 852, p. 9–20, Pl. 7.
98. Foster, H. L. (1947) *Paleozoic and Mesozoic stratigraphy of northern Gros Ventre Mountains and Mount Leidy Highlands, Teton County, Wyoming*, Am. Assoc. Petrol. Geol., Bull., vol. 31, p. 1568–1592.
99. Fox, S. K., Jr., and Ross, R. J., Jr. (1942) *Foraminiferal evidence for the Midway (Paleocene) age of the Cannonball formation in North Dakota*, Jour. Paleont., vol. 16, p. 660–673.
100. Fuenning, Paul (1942) *Thickness and structural study of major divisions of the Cretaceous system in Nebraska*, Am. Assoc. Petrol. Geol., Bull., vol. 26, p. 1517–1536.
101. Gale, H. S. (1908) *Geology of the Rangely oil district, Rio Blanco County, Colorado*, U. S. Geol. Survey, Bull. 350, p. 13–25.
102. Gardner, J. H. (1910) *The Carthage coal field, New Mexico*, U. S. Geol. Survey, Bull. 381, p. 455.
103. Gardner, L. S. (1947) *Phosphate deposits of the Teton Basin area, Idaho and Wyoming*, U. S. Geol. Survey, Bull. 944, p. 5–7.
104. Garrett, D. L., (1920) *Stratigraphy and structure of northeastern New Mexico*, Am. Assoc. Petrol. Geol., Bull., vol. 4, p. 73–82.
105. Gilbert, G. K. (1877) *Report on the geology of the Henry Mountains*, U. S. Geog. Geol. Survey Rocky Mtn. Region, Rept., p. 4, 12.
106. —— (1896) *The underground water of the Arkansas Valley in eastern Colorado*, U. S. Geol. Survey, Ann. Rept. 17, p. 564, 565, Pl. 2.
107. —— (1897) *Pueblo quadrangle, Colorado*, U. S. Geol. Survey, Geol. Atlas, Folio 68.
108. Gilmore, C. W. (1916) *Vertebrate faunas of the Ojo Alamo, Kirtland, and Fruitland formations*, U. S. Geol. Survey, Prof. Paper 98, p. 279–308.
109. —— (1919) *Reptilian faunas of the Torrejon, Puerco, and underlying Upper Cretaceous formations of San Juan County, New Mexico*, U. S. Geol. Survey, Prof. Paper 119, 71 pages.
110. —— (1947) *Reptilian fauna of the North Horn formation, Utah*, U. S. Geol. Survey, Prof. Paper 210-C, p. 29–53.
111. Gould, C. N. (1928) *The Benton Cretaceous in Oklahoma*, Okla. Univ., Bull., n. ser., no. 410, p. 141–143.
112. Gregory, H. E. (1917) *Geology of the Navajo Country*, U. S. Geol. Survey, Prof. Paper 93, p. 72–75.
113. —— (1950 [1952]) *Geology and geography of the Zion Park region, Utah and Arizona*, U. S. Geol. Survey, Prof. Paper 220, 200 pages.
114. —— and Moore, R. C. (1931) *The Kaiparowits region*, U. S. Geol. Survey, Prof. Paper 164, p. 37, 94–113, Pl. 5.
115. ——; Thorpe, M. R.; and Miser, H. D. (1938) *The San Juan Country*, U. S. Geol. Survey, Prof. Paper 188, p. 60–63.
116. Gries, J. P. (1940) *Structural study of northeastern Stanley County, South Dakota*, S. D. Geol. Survey, Rept. Invest. 34, p. 8–35.
117. —— and Rothrock, E. P. (1941) *Manganese deposits of the lower Missouri Valley in South Dakota*, S. D. Geol. Survey, Rept. Invest. 38, p. 6–30.
118. Griffitts, M. O. (1949) *Zones of Pierre formation of Colorado*, Am. Assoc. Petrol. Geol., Bull., vol. 33, p. 2011–2028.
119. Grinnell, G. B. (1876) *On a new crinoid from the Cretaceous formation of the West*, Am. Jour. Sci., 3d ser., vol. 12, p. 81–83.
120. Haas, Otto (1949) *Acanthoceratid Ammonoidea from near Greybull, Wyoming*, Am. Mus. Nat. Hist., Bull., vol. 93, art. 1, p. 1–40.
121. —— (1951) *Supplementary notes on the ammonite genus Dunveganoceras*, Am. Mus. Novitates, no. 1491.
122. Hall, C. W.; Meinzer, O. E.; and Fuller, M. L. (1911) *Geology and underground waters of southern Minnesota*, U. S. Geol. Survey, W.-S. Paper 256, p. 132–138, 144, 223, 240, 267, 281, 381.
123. Hall, James, and Meek, F. B. (1856) *Descriptions of new species of fossils from the Cretaceous formations of Nebraska*, etc., Am. Acad. Arts and Sci., Mem., n. ser., vol. 5, p. 379–411.
124. Hancock, E. T. (1918) *Geology and oil and gas prospects of the Lake Basin field, Montana*, U. S. Geol. Survey, Bull. 691, p. 107–129, Pl. 17.
125. —— (1921) *The Lance Creek oil and gas field, Niobrara County, Wyoming*, U. S. Geol. Survey, Bull. 716, p. 94–105.
126. —— and Eby, J. B. (1930) *Geology and coal resources of the Meeker quadrangle, Moffat and Rio Blanco Counties, Colorado*, U. S. Geol. Survey, Bull. 812, p. 197–208.
127. Hares, C. J. (1916) *Anticlines in central Wyoming*, U. S. Geol. Survey, Bull. 641, p. 238, 244–247.
128. —— and others (1946) *Geologic map of the southern part of the Wind River Basin and adjacent areas in central Wyoming*, U. S. Geol. Survey, Oil and Gas Invest., Prelim. Map 60.
129. Haug, Emile (1909–1911) *Traité de Géologie*, tome 2, fasc. 2, p. 1153–1396.
130. Heald, K. C. (1927) *The geology of the Ingomar anticline, Treasure and Rosebud counties, Montana*, U. S. Geol. Survey, Bull. 786.
131. Henderson, Junius (1908) *New species of Cretaceous invertebrates from northern Colorado*, U. S. Nat. Mus., Pr., vol. 34, no. 1611, p. 259–264.
132. —— (1913) *in* Grout, F. F.; Worcester, P. G.; and Henderson, Junius: *Reconnaissance of the geology of the Rabbit Ears region*, Colo. Geol. Survey, Bull. 5, pt. 1, p. 22, 28–34.
133. —— (1934) *Some new Mesozoic Mollusca from the Rocky Mountain region and Arizona*, Jour. Paleont., vol. 8, p. 259–263.
134. Hewett, D. F. (1914) *The Shoshone River section, Wyoming*, U. S. Geol. Survey, Bull. 541, p. 91, 96–104.
135. —— and Lupton, C. T. (1917) *Anticlines in the southern part of the Bighorn Basin, Wyoming*, U. S. Geol. Survey, Bull. 656, p. 16, 19–28, 112–119.
136. —— and others (1936) *Mineral resources of the*

region around Boulder Dam, U. S. Geol. Survey, Bull. 871, p. 119–122.

137. Hills, R. C. (1899) *Elmoro quadrangle, Colorado*, U. S. Geol. Survey, Geol. Atlas, Folio 58.
138. —— (1900) *Walsenberg quadrangle, Colorado*, U. S. Geol. Survey, Geol. Atlas, Folio 68.
139. —— (1901) *Spanish Peaks quadrangle, Colorado*, U. S. Geol. Survey, Geol. Atlas, Folio 71.
140. Horberg, Leland (1938) *The structural geology and physiography of the Teton Pass area, Wyoming*, Augustana Library, Pub. 16, p. 1–86.
141. Huddle, J. W., and McCann, F. T. (1947) *Pre-Tertiary geology of the Duchesne River area, Duchesne and Wasatch counties, Utah*, U. S. Geol. Survey Oil and Gas Invest., Prelim. Map 75.
142. Hunt, C. B. (1936) *Geology and fuel resources of the southern part of the San Juan Basin, New Mexico; part 2, The Mount Taylor coal field*, U. S. Geol. Survey, Bull. 860-B, p. 39–50.
143. —— (1946) *Guidebook to the geology and geography of the Henry Mountains region*, Utah Geol. Soc., Guidebook 1.
144. Hyatt, Alpheus (1894) *Phylogeny of an acquired characteristic*, Am. Philos. Soc., Pr., vol. 32, p. 349–647.
145. —— (1903) *Pseudoceratites of the Cretaceous*, U. S. Geol. Survey, Mon. 44.
146. Imlay, R. W. (1944) *Correlation of the Cretaceous formations of the Greater Antilles, Central America, and Mexico*, Geol. Soc. Am., Bull., vol. 55, p. 1005–1045.
147. Jeletzky, J. A. (1951a) *Die Stratigraphie und Belemnitenfauna des Obercampan und Maastricht Westfalens, Nordwestdeutschlands und Danemarks sowie einige allgemeine Gliederungs-Probleme der jüngeren borealen Oberkreide Eurasiens*, Bundesrep. Deutschland, Geol. Landesanstalt, Geol. Jahrb., Beihefte, Heft 1.
148. —— (1951b) *The place of the Trimingham and Norwich chalk in the Campanian-Maestrichtian succession*, Geol. Mag., vol. 88, p. 197–208.
149. Jensen, F. S. (1951) *Preliminary report on the geology of the Nashua quadrangle [Valley and McCone counties, Montana]*, U. S. Geol. Survey, Open-file Rept.
150. Johnson, J. H. (1930) *Unconformity in Colorado group in eastern Colorado*, Am. Assoc. Petrol. Geol., Bull., vol. 14, p. 789–794.
151. —— (1935) *Stratigraphy of South Park (abstract)*, Geol. Soc. Am., Pr. 1934, p. 86.
152. Katich, P. J. (1951) *Recent evidence for Lower Cretaceous deposits in Colorado Plateau*, Am. Assoc. Petrol. Geol., Bull., vol. 35, p. 2093.
153. Kirk, S. R. (1930) *Cretaceous stratigraphy of the Manitoba escarpment*, Geol. Survey Canada, Summ. Rept. for 1929, pt. B, p. 112–135.
154. Klepper, M. R. (1950) *A geologic reconnaissance of parts of Beaverhead and Madison Counties, Montana*, U. S. Geol. Survey, Bull. 969, p. 55–85.
155. Kloos, J. H. (1872) *A Cretaceous basin in the Sauk Valley, Minnesota*, Am. Jour. Sci., 3d ser., vol. 3, p. 17–26.
156. Knappen, R. S., and Moulton, G. F. (1931) *Geology and mineral resources of parts of Carbon, Big Horn, Yellowstone, and Stillwater counties, Montana*, U. S. Geol. Survey, Bull. 822, p. 7–9, 20–50.
157. Knechtel, M. M. (1944) *Oil and gas possibilities of the plains adjacent to the Little Rocky Mountains, Montana*, U. S. Geol. Survey, Oil and Gas Invest., Prelim. Map 4.
158. Kramer, W. B.; Dobbin, C. E.; and McMillan, Robert (1944) *Geologic map and sections of Lance Creek oil and gas field and vicinity, Niobrara County, Wyoming*, U. S. Geol. Survey.
159. Laird, W. M. (1941) *Selected deep well records*, N. D. Geol. Survey, Bull. 12, p. 4–27.
160. —— (1946) *The subsurface stratigraphy of the Nesson anticline*, N. D. Geol. Survey, Bull. 21, pt. 2, p. 13–25.
161. —— and Mitchell, R. H. (1942) *The geology of the southern part of Morton County, North Dakota*, N. D. Geol. Survey, Bull. 14.
162. Landes, R. W. (1940) *Paleontology of the marine formations of the Montana group*, Geol. Survey Canada, Mem. 221, pt. 2, p. 129–217.
163. Lasky, S. G. (1936) *Geology and ore deposits of the Bayard area, Central mining district, New Mexico*, U. S. Geol. Survey, Bull. 870, p. 19–26.
164. —— (1938) *Newly discovered section of Trinity age in southwestern New Mexico*, Am. Assoc. Petrol. Geol., Bull., vol. 22, p. 524–540.
165. —— (1947) *Geology and ore deposits of the Little Hatchet Mountains, Hidalgo and Grant Counties, New Mexico*, U. S. Geol. Survey, Prof. Paper 208, 101 pages.
166. Lavington, C. S. (1933) *Montana group in eastern Colorado*, Am. Assoc. Petrol. Geol., Bull., vol. 17, p. 397–410.
167. Lee, W. T. (1906a) *The Engle coal field, New Mexico*, U. S. Geol. Survey, Bull. 285, p. 240.
168. —— (1906b) *Note on the red beds of the Rio Grande region in central New Mexico*, Jour. Geol., vol. 15, p. 52–58.
169. —— (1912) *Coal fields of Grand Mesa and the West Elk Mountains, Colorado*, U. S. Geol. Bull. 510, p. 18–21, 23–47.
170. —— (1924) *Coal resources of the Raton coal field, Colfax County, New Mexico*, U. S. Geol. Survey, Bull. 752, p. 121.
171. —— (1927) *Correlation of geologic formations between east-central Colorado, central Wyoming, and southern Montana*, U. S. Geol. Survey, Prof. Paper 149, p. 17, 20, 31–44.
172. —— and Knowlton, F. H. (1917) *Geology and paleontology of the Raton Mesa and other regions in Colorado and New Mexico*, U. S. Geol. Survey, Prof. Paper 101, p. 40, 179, 184, 206–217.
173. Leith, C. K. (1903) *The Mesabi iron-bearing district of Minnesota*, U. S. Geol. Survey, Mon. 43, p. 190–191.
174. —— and Harder, E. C. (1908) *The iron ores of the Iron Springs district, southern Utah*, U. S. Geol. Survey, Bull. 338, p. 37–40.
175. Leonard, A. C. (1912) *Bismarck quadrangle, South Dakota*, U. S. Geol. Survey, Geol. Atlas, Folio 181.
176. Lindgren, Waldemar (1905a) *Clifton quad-*

range, Arizona, U. S. Geol. Survey, Geol. Atlas, Folio 129.

177. —— (1905b) *The copper deposists of the Clifton-Morenci district, Arizona*, U. S. Geol. Survey, Prof. Paper 43, 375 pages.

178. Littlefield, Max (1939) *Log of wildcat well in Pennington County, South Dakota*, Am. Assoc. Petrol. Geol., Bull., vol. 23, p. 1234–1237.

179. Lloyd, E. R. (1914) *The Cannonball River lignite field, Morton, Adams, and Hettinger Counties, North Dakota*, U. S. Geol. Survey, Bull. 541, p. 248–250.

180. Longwell, C. R. (1928) *Geology of the Muddy Mountains, Nevada*, U. S. Geol. Survey, Bull. 798, p. 21, 68–74.

181. Love, J. D. (1928) *Geology along the southern margin of the Absaroka Range, Wyoming*, Geol. Soc. Am., Spec. Paper 20, p. 10–12, 54–58.

182. —— and others (1945) *Stratigraphic sections and thickness maps of Lower Cretaceous and nonmarine Jurassic rocks of central Wyoming*, U. S. Geol. Survey, Oil and Gas Invest., Prelim. Chart 13.

183. —— —— —— (1947) *Stratigraphic sections of Mesozoic rocks in central Wyoming*, Geol. Survey Wyo., Bull. 38, 59 pages.

184. —— —— —— (1948) *Stratigraphic sections of Jurassic and Cretaceous rocks in the Jackson Hole area, Wyoming*, Geol. Survey Wyo., Bull. 40, 48 pages.

185. —— —— —— (1951a) *Geologic map of the Spread Creek-Gros Ventre River area, Teton County, Wyoming*, U. S. Geol. Survey, Oil and Gas Invest., Map OM 118.

186. —— —— —— (1951b) *Stratigraphic sections of Cretaceous rocks in northeastern Teton County, Wyoming*, U. S. Geol. Survey, Oil and Gas Invest., Chart OC 43.

187. Lovering, T. S. (1931) *The Granby anticline, Grand County, Colorado*, U. S. Geol. Survey, Bull. 822, p. 71–76.

188. —— (1934) *Geology and ore deposits of the Breckenridge district, Colorado*, U. S. Geol. Survey, Prof. Paper 176, p. 7–14, Pl. 3.

189. —— and Goddard, E. N. (1950) *Geology and ore deposits of the Front Range, Colorado*, U. S. Geol. Survey, Prof. Paper 223, p. 38–40.

190. Lull, R. S. (1933) *A revision of the Ceratopsia or horned dinosaurs*, Peabody Mus. Nat. Hist., Mem., vol. 3, 175 pages.

191. Lupton, C. T. (1912) *The Blacktail (Tabby) Mountain coal field, Wasatch County, Utah*, U. S. Geol. Survey, Bull. 471, p. 603, 608–612.

192. —— (1916a) *Oil and gas near Basin, Big Horn County, Wyoming*, U. S. Geol. Survey, Bull. 621, p. 166–174.

193. —— (1916b) *Geology and coal resources of Castle Valley in Carbon, Emery, and Sevier counties, Utah*, U. S. Geol. Survey, Bull. 628, p. 26–30.

194. Lyons, J. B. (1944) *Igneous rocks of the northern Big Belt Range, Montana*, Geol. Soc. Am., Bull., vol. 55, p. 449, 451–452.

195. MacBride, T. H. (1901) *Clay and Obrien counties*, Iowa Geol. Survey, Repts., vol. 11, p. 461–497.

196. Mackin, J. H. (1947) *Some structural features of the intrusions in the Iron Springs district [Utah]*, Utah Geol. Soc., Guide Book 12.

197. MacNeil, F. S. (1939) *Fresh-water invertebrates and land plants of Cretaceous age from Eureka, Nevada*, Jour. Paleont., vol. 13, p. 355–360.

198. Mansfield, G. R. (1920) *Coal in eastern Idaho*, U. S. Geol. Survey, Bull. 716, p. 128–130.

199. —— (1927) *Geography, geology, and natural resources of part of southeastern Idaho*, U. S. Geol. Survey, Prof. Paper 152, p. 105–108.

200. —— and Roundy, P. V. (1916) *Revision of Beckwith and Bear River formations of southeastern Idaho*, U. S. Geol. Survey, Prof. Paper 98, p. 75–84.

201. Mather, K. F., and others (1928) *Geology and oil and gas prospects of northeastern Colorado*, U. S. Geol. Survey, Bull. 796, p. 76–100, 111–113, Text-fig. 7, Pl. 18.

202. Mathews, A. A. L. (1931) *Mesozoic stratigraphy of the central Wasatch Mountains*, Oberlin Coll., Lab. Bull., n. ser., no. 1, p. 48–50.

203. —— *in* Boutwell, J. M. (1933) *The Salt Lake region*, 16th Inter. Geol. Cong., Guidebook 17, p. 58, 59.

204. McGee, W J (1891) *The Pleistocene history of northeastern Iowa*, U. S. Geol. Survey, 11th Ann. Rept., pt. 1, p. 304–308.

205. McLaughlin, T. G. (1942) *Geology and ground water resources of Morton County, Kansas*, Kans. State Geol. Survey, Bull. 40, 126 pages.

206. McLearn, F. H. (1929) *Cretaceous invertebrates* and *Stratigraphic paleontoloty [of Blairmore district, Alberta]*, Nat. Mus. Canada, Bull. 58, p. 73–107.

207. —— (1931) *The* Gastroplites *and other Lower Cretaceous faunas of the northern Great Plains*, Roy. Soc. Canada, Tr., ser. 3, vol. 25, sec. 4, p. 1–8.

208. —— (1933) *The ammonoid genera* Gastroplites *and* Neogastroplites, Roy. Soc. Canada, Tr., ser. 3, vol. 27, sec. 4, p. 13–25.

209. —— (1937) *The fossil zones of the Upper Cretaceous Alberta shale*, Roy. Soc. Canada, Tr., ser. 3, vol. 31, sec. 4, p. 111–120.

210. —— (1945) *Revision of the Lower Cretaceous of the western interior of Canada*, Geol. Survey Canada, Paper 44–17, 2d ed.

211. Meek, F. B. (1876) *A report on the invertebrate Cretaceous and Tertiary fossils of the Upper Missouri Country*, U. S. Geol. Survey Terr., Rept., vol. 9, 629 pages.

212. —— (1877) *Paleontology—Cretaceous species*, U. S. Geol. Expl. 40th Par., Rept., vol. 4, pt. 1, p. 140–182.

213. —— and Hayden, F. V. (1856) *Descriptions of new species of Gastropoda from the Cretaceous formations of Nebraska Territory*, Acad. Nat. Sci. Philadelphia, Pr., vol. 8, p. 63.

214. —— —— —— (1861) *Descriptions of new Lower Silurian (Primordial), Jurassic, Cretaceous, and Tertiary fossils collected in Nebraska Terr. . . . , with some remarks on the rocks from which they were obtained*, Acad. Nat. Sci. Philadelphia, Pr. 1861, vol. 13, p. 417–432.

215. Moody, J. D. (1947) *Upper Montana group, Golden area, Jefferson County, Colorado*, Am. Assoc. Petrol. Geol., Bull., vol. 31, p. 1454–1471.

216. Moore, R. C. (1949) *Meaning of facies*, in

Sedimentary facies in geologic history, Geol. Soc. Am., Mem. 39, p. 27.

217. Morgan, R. E., and Petsch, B. C. (1945) *A geological survey in Dewey and Corson counties, South Dakota*, S. D. Geol. Survey, Rept. Invest. 49, p. 12–18.
218. Morrow, A. L. (1935) *Cephalopods from the Upper Cretaceous of Kansas*, Jour. Paleont., vol. 9, p. 463–473.
219. Morton, S. G. (1842) *Description of some new species of organic remains of the Cretaceous group of the United States...*, Acad. Nat. Sci. Philadelphia, Jour., ser. 1, vol. 8, p. 209.
220. Muller, S. G., and Schenck, H. G. (1943) *Standard of the Cretaceous system*, Am. Assoc. Petrol. Geol., Bull., vol. 27, p. 262–278.
221. Northrop, S. A., and others (1946) *Geologic maps of a part of the Las Vegas Basin and of the foothills of the Sangre de Cristo Mountains, New Mexico*, U. S. Geol. Survey, Oil and Gas Invest., Prelim. Map 54.
222. Owen, D. D. (1852) *Report of a geological survey of Wisconsin, Iowa, and Minnesota and incidentally of a portion of Nebraska Territory*, Lippincott, Grambo, and Co., Philadelphia.
223. Paige, Sidney (1916) *Silver City quadrangle, New Mexico*, U. S. Geol. Survey, Geol. Atlas, Folio 199.
224. Pardee, J. T. (1917) *The Garrison and Philipsburg phosphate fields, Montana*, U. S. Geol. Survey, Bull. 640, p. 202, 211, 212.
225. —— and Schrader, F. C. (1933) *Metalliferous deposits of the Greater Helena mining region, Montana*, U. S. Geol. Survey, Bull. 842, p. 13–14.
226. Patton, H. B. (1924) *Underground water possibilities for stock and domestic purposes in the La Junta area, Colorado*, Colo. Geol. Survey, Bull. 27, pt. 1, p. 14–21.
227. Peale, A. C. (1896) *Three Forks quadrangle, Montana*, U. S. Geol. Survey, Geol. Atlas, Folio 24.
228. Peck, R. E. (1941) *Lower Cretaceous Rocky Mountain nonmarine fossils*, Jour. Paleont., vol. 15, p. 285–289.
229. —— (1951) *Nonmarine ostracodes—the subfamily Cyprideinae in the Rocky Mountain area*, Jour. Paleont., vol. 25, p. 307–320.
230. Pervinquière, Léon (1907) *Céphalopodes des terrains secondaires*, Carte géol. Tunisie, Études de paléontologie tunisienne, pt. 1. p. 339–348.
231. Petsch, B. C. (1942) *The Medicine Butte anticline*, S. D. Geol. Survey, Rept. Invest. 45, Appendix, p. 6, 7, Fig. 6E.
232. —— (1949) *North part of Whitewood anticline*, S. D. Geol. Survey, Rept. Invest. 65.
233. Pierce, W. G., and Andrews, D. A. (1941) *Geology and coal and oil resources of the region south of Cody, Park County, Wyoming*, U. S. Geol. Survey, Bull. 921-B, p. 109, 113–134.
234. Pike, W. S., Jr. (1947) *Intertonguing marine and nonmarine Upper Cretaceous deposits of New Mexico, Arizona, and southwestern Colorado*, Geol. Soc. Am., Mem. 41, 103 pages.
235. Plummer, Norman, and Romary, J. F. (1942) *Stratigraphy of the pre-Greenhorn Cretaceous beds of Kansas*, Kans. Geol. Survey, Bull. 41, pt. 9, p. 313–348.
236. Rae, C. C. (1928) *Big Sand Draw field, Fremont County, Wyoming*, Am. Assoc. Petrol. Geol., Bull., vol. 12, p. 1139–1141.
237. Rankin, C. H., Jr. (1933) *Study of well sections in northeastern Colorado*, Am. Assoc. Petrol. Geol., Bull., vol. 17, p. 423.
238. —— (1944) *Stratigraphy of the Colorado group, Upper Cretaceous, in northern New Mexico*, N. Mex. State Bur. Mines Min. Res., Bull. 20, 30 pages.
239. Ransome, F. L. (1904) *The geology and ore deposits of the Bisbee quadrangle, Arizona*, U. S. Geol. Survey, Prof. Paper 21, p. 60–61.
240. —— (1919) *The copper deposits of Ray and Miami, Arizona*, U. S. Geol. Survey, Prof. Paper 115, p. 56–57.
241. Read, C. B., and Brown, R. W. (1937) *American Cretaceous ferns of the genus* Tempskya, U. S. Geol. Survey, Prof. Paper 186-F, p. 126–127, Pl. 27.
242. Reed, E. C. (1938) *Correlation of formations drilled in the Midland Forster well near Fremont, Nebraska*, Nebr. Geol. Survey, Paper 13.
243. Reeside, J. B., Jr. (1923a) *The fauna of the so-called Dakota formation of north-central Colorado and its equivalent in southeastern Wyoming*, U. S. Geol. Survey, Prof. Paper 131, p. 199–207.
244. —— (1923b) *A new fauna from the Colorado group of southern Montana*, U. S. Geol. Survey, Prof. Paper 132, p. 25–46.
245. —— (1924) *Upper Cretaceous and Tertiary formations of the western part of the San Juan Basin, Colorado and New Mexico*, U. S. Geol. Survey, Prof. Paper 134, p. 4–35, 56, 62–65.
246. —— (1927a) *The cephalopods of the Eagle sandstone and related formations in the western interior of the United States*, U. S. Geol. Survey, Prof. Paper 151, 87 pages.
247. —— (1927b) *Cephalopods from the lower part of the Cody shale of Oregon Basin, Wyoming*, U. S. Geol. Survey, Prof. Paper 150, p. 1–19.
248. —— (1929a) *Deep well for oil in east-central North Dakota*, U. S. Dept. Interior, Memo. for the Press 29777.
249. —— (1929b) Exogyra olisiponensis *Sharpe* and Exogyra costata *Say* in the *Cretaceous of the Western Interior*, U. S. Geol. Survey, Prof. Paper 154, p. 267–278.
250. —— (1930) *The Cretaceous faunas in the section on Vermilion Creek, Moffat County, Colorado*, Washington Acad. Sci., Jour., vol. 20, p. 35–41.
251. —— (1932) *The Upper Cretaceous ammonite genus* Barroisiceras *in the United States*, U. S. Geol. Survey, Prof. Paper 170, p. 9–29.
252. —— and Baker, A. A. (1929) *The Cretaceous section in Black Mesa, northeastern Arizona*, Washington Acad. Sci., Jour., vol. 19, p. 30–37.
253. Reeves, Frank (1924) *Geology and possible oil and gas resources of the faulted area south of the Bearpaw Mountains, Montana*, U. S. Geol. Survey, Bull. 751, p. 73–93.
254. —— (1927) *Geology of the Cat Creek and Devils Basin oil fields and adjacent areas in Montana*, U. S. Geol. Survey, Bull. 786, p. 43–47.

255. —— (1929) *Thrust faulting and oil possibilities in the plains adjacent to the Highwood Mountains, Montana*, U. S. Geol. Survey, Bull. 806, p. 158–163.
256. —— (1931) *Geology of the Big Snowy Mountains, Montana*, U. S. Geol. Survey, Prof. Paper 165, p. 136–139.
257. Richards, P. W., and Rogers, C. P., Jr. (1951) *Geology of the Hardin area, Big Horn and Yellowstone counties, Montana*, U. S. Geol. Survey, Oil and Gas Invest., Map OM 111.
258. Richardson, G. B. (1927) *The Upper Cretaceous section in the Colob Plateau, southwest Utah*, Washington Acad. Sci., Jour., vol. 17, p. 464–475.
259. Roemer, Ferdinand (1852) *Die Kreidebildungen von Texas und ihre organischen Einschlüsse*, Bonn.
260. Rogers, G. S. (1914) *Geology and coal resources of the area southwest of Custer, Yellowstone, and Big Horn counties, Montana*, U. S. Geol. Survey, Bull. 541, p. 319–320.
261. Ross, C. P. (1925) *Geology and ore deposits of the Aravaipi and Stanley mining districts, Graham County, Arizona*, U. S. Geol. Survey, Bull. 763, p. 25–29.
262. Rothrock, E. P. (1936) *Logs of some deep wells in western South Dakota*, S. D. State Geol. Survey, Rept. Invest. 4, p. 3, 34.
263. Rubey, W. W. (1929) *Origin of the siliceous Mowry shale of the Black Hills region*, U. S. Geol. Survey, Prof. Paper 154, p. 153–170.
264. —— (1931) *Lithologic studies of fine-grained Upper Cretaceous sedimentary rocks of the Black Hills region*, U. S. Geol. Survey, Prof. Paper 165, p. 3–5.
265. —— and Bass, N. W. (1925) *The geology of Russell County, Kansas*, Kans. Geol. Survey, Bull. 10, p. 16, 17, 25–65.
266. Russell, W. L. (1926) *The possibilities of oil in western Corson County*, S. D. Geol. Nat. Hist. Survey, Circ. 27, p. 5–11.
267. —— (1930) *The possibilities of oil and gas in western Potter County*, S. D. Geol. Nat Hist. Survey, Rept. Invest. 7, 14 pages.
268. Sardeson, F. W. (1908) *Geological history of the Redstone quartzite*, Geol. Soc. Am., Bull., vol. 19, p. 222–224.
269. Schlaikjer, E. M. (1935) *The Torrington member of the Lance formation and a study of a new Triceratops*, Harvard College, Mus. Comp. Zool., Bull., vol. 76, no. 2, p. 31–53.
270. Schoff, S. L. (1938) *Geology of the Cedar Hills, Utah*, Ohio State Univ., Abstr. Doct. Dissert., no. 25, p. 375–386.
271. —— (1951) *Geology of the Cedar Hills, Utah*, Geol. Soc. Am., Bull., vol. 62, p. 619–646.
272. —— and Stovall, J. W. (1943) *Geology and ground water resources of Cimarron County, Oklahoma*, Okla. Geol. Survey, Bull. 64, 317 pages.
273. Schrader, F. C. (1915) *Mineral deposits of the Santa Rita and Patagonia Mountains, Arizona*, U. S. Geol. Survey, Bull. 582, p. 54–56.
274. Schultz, A. R. (1910) *The southern part of the Rock Springs coal field, Sweetwater County, Wyoming*, U. S. Geol. Survey, Bull. 381, p. 222–223.
275. —— (1918) *A geologic reconnaissance for phosphate and coal in southeastern Idaho and western Wyoming*, U. S. Geol. Survey, Bull. 680, p. 26–29.
276. Scott, Gayle (1940) *Cephalopods from the Cretaceous Trinity group of the south-central United States*, Univ. Texas, Pub. 3945, p. 969–1106.
277. Searight, W. V. (1937) *Lithologic stratigraphy of the Pierre formation of the Missouri Valley in South Dakota*, S. D. State Geol. Survey, Rept. Invest. 27, 63 pages.
278. —— *in* Moxon, A. L.; Olson, O. E.; and Searight, W. V. (1939) *Selenium in rocks, soils, and plants*, S. D. State Coll. Agric. Mech. Arts, Tech. Bull. 2, p. 11–26.
279. Sears, J. D. (1924) *Geology and oil and gas prospects of part of Moffat County, Colorado, and southern Sweetwater County, Wyoming*, U. S. Geol. Survey, Bull. 751, p. 278–281.
280. —— (1925) *Geology and coal resources of the Gallup-Zuni Basin, New Mexico*, U. S. Geol. Survey, Bull. 767, p. 8, 13–18.
281. —— (1926) *Geology of the Baxter Basin gas field, Sweetwater County, Wyoming*, U. S. Geol. Survey, Bull. 781, p. 16–21, Pls. 5, 6.
282. —— (1934) *Geology and fuel resources of the southern part of the San Juan Basin, New Mexico; part I, The coal field from Gallup eastward toward Mount Taylor*, U. S. Geol. Survey, Bull. 860-A, p. 11–19.
283. ——; Hunt, C. B.; and Hendricks, T. A. (1941) *Transgressive and regressive deposits in southern San Juan Basin, New Mexico*, U. S. Geol. Survey, Prof. Paper 193, p. 101–121.
284. Sharkey, H. H. R., and others (1946) *Geologic and structure contour map of Sage Creek dome, Fremont County, Wyoming*, U. S. Geol. Survey, Oil and Gas Invest., Prelim. Map 53.
285. Sidwell, Raymond (1932) *New species from the Colorado group, Cretaceous, in south-central Wyoming*, Jour. Paleont., vol. 6, p. 312–318.
286. Smith, C. D. (1910) *The Fort Peck Indian Reservation lignite field, Montana*, U. S. Geol. Survey, Bull. 381, p. 40–59.
287. Spath, L. F. (1941) *On the boundary between the Upper and Lower Cretaceous*, Geol. Mag., vol. 78, p. 309–315.
288. Spencer, A. C., and Paige, Sidney (1935) *Geology of the Santa Rita mining area, New Mexico*, U. S. Geol. Survey, Bull. 859, p. 28–31.
289. Spieker, E. M. (1931) *The Wasatch Plateau coal field, Utah*, U. S. Geol. Survey, Bull. 819, p. 16–45, Pl. 3.
290. —— (1946) *Late Mesozoic and early Tertiary history of central Utah*, U. S. Geol. Survey, Prof. Paper 205-D, p. 117–161.
291. —— and Schoff, S. L. (1937) *Orogenic chronology of central Utah* (Abstract), Geol. Soc. Am., Pr. 1936, p. 104.
292. Stanton, T. W. (1893) *The Colorado fauna*, U. S. Geol. Survey, Bull. 106.
293. —— (1899) *Mesozoic fossils [of Yellowstone National Park]*, U. S. Geol. Survey, Mon. 32, p. 600–652.
294. —— (1903) *A new fresh-water faunule from the Cretaceous of Montana*, Am. Philos. Soc., Pr., vol. 142, no. 173, p. 188–199.
295. —— (1905) *Morrison formation and its rela-*

tions with the Comanche series and the Dakota formation, Jour. Geol., vol. 13, p. 665.

296. Stanton, T. W. (1920) *The fauna of the Cannonball marine member of the Lance formation*, U. S. Geol. Survey, Prof. Paper 128-A, p. 1–66.
297. —— (1922) *Some problems connected with the Dakota sandstone*, Geol. Soc. Am., Bull., vol. 33, p. 255–272.
298. ——; Hatcher, J. B.; and Knowlton, F. H. (1905) *Geology and paleontology of the Judith River beds*, U. S. Geol. Survey, Bull. 257, 174 pages.
299. Stark, J. T., and others (1949) *Geology and origin of South Park, Colorado*, Geol. Soc. Am., Mem. 33, 188 pages.
300. Stauffer, C. R., and Thiel, G. A. (1933) *The limestones and marls of Minnesota*, Minn. Geol. Survey, Bull. 23, p. 18.
301. —— —— —— (1941) *The Paleozoic and related rocks of southeastern Minnesota*, Minn. Geol. Survey, Bull. 29, p. 102–106, 175.
302. Stearns, C. E. (1943) *The Galisteo formation of north-central New Mexico*, Jour. Geol., vol. 51, p. 301–319.
303. Stebinger, Eugene (1917) *Anticlines in the Blackfeet Indian Reservation, Montana*, U. S. Geol. Survey, Bull. 641, p. 284–291.
304. —— (1918) *Oil and gas geology of the Birch Creek-Sun River area, northwestern Montana*, U. S. Geol. Survey, Bull. 691, p. 149–184.
305. Stephenson, L. W. (1937) *Stratigraphic relations of the Austin, Taylor, and equivalent formations in Texas*, U. S. Geol. Survey, Prof. Paper 186, p. 133–146.
306. —— (1941) *The larger invertebrate fossils of the Navarro group of Texas*, Univ. Texas, Pub. 4101, 641 pages.
307. —— (1952) *The larger invertebrate fossils of the Woodbine formation (Cenomanian) of Texas*, U. S. Geol. Survey, Prof. Paper 242, 235 pages.
308. —— and Reeside, J. B., Jr. (1938) *Comparison of Upper Cretaceous deposits of Gulf Region and western interior region*, Am. Assoc. Petrol. Geol., Bull., vol. 22, p. 1629–1638.
309. Stokes, W. L. (1944) *Morrison formation and related deposits in and adjacent to the Colorado Plateau*, Geol. Soc. Am., Bull., vol. 55, p. 965–970.
310. —— and Phoenix, D. A. (1948) *Geology of the Egnar-Gypsum Valley area, San Miguel and Montrose counties, Colorado*, U. S. Geol. Survey, Oil and Gas Invest., Prelim. Map 93.
311. Stone, W. R., and Calvert, W. R. (1910) *Stratigraphic relations of the Livingston formation, Montana*, Econ. Geol., vol. 5, p. 551–557, 652–669, 741–764.
312. Stose, G. W. (*Editor*) (1946) *Geologic map of North America*, Geol. Soc. Am.
313. Stovall, Willis (1943) *in* Schoff, S. L.: *Geology and ground water resources of Cimarron County, Oklahoma*, Okla. Geol. Survey, Bull. 64, p. 43–100.
314. Stoyanow, A. A. (1937) *Fossiliferous zones in the Cretaceous and Tertiary deposits of southeastern Arizona* (Abstract), Geol. Soc. Am., Pr. 1936, p. 296.
315. —— (1938) *Lower Cretaceous stratigraphy in southeastern Arizona* (Abstract), Geol. Soc. Am., Pr. 1937, p. 117.
316. —— (1949) *Lower Cretaceous stratigraphy in southeastern Arizona*, Geol. Soc. Am., Mem. 38, 156 pages.
317. Tate, Ralph (1865) *Correlation of the Cretaceous formations of the northeast of Ireland*, Geol. Soc. London, Quart. Jour., vol. 21, p. 15–44.
318. Tester, A. C. (1931) *The Dakota stage of the type locality*, Iowa Geol. Survey, Ann. Rept., vol. 35, p. 235–238, 252–253, 255, 261.
319. Thom, W. T., Jr., and Reeside, J. B., Jr. (1923) *Possible oil and gas in northwestern North Dakota*, U. S. Dept. Interior, Memo. for the Press 3761.
320. —— — Spieker, E. M. (1931) *The significance of geologic conditions in Naval Petroleum Reserve No. 3, Wyoming*, U. S. Geol. Survey, Prof. Paper 163, p. 11–16.
321. ——; Hall, G. M.; Wegemann, C. H.; and Moulton, G. F. (1935) *Geology of Big Horn County and the Crow Indian Reservation, Montana*, U. S. Geol. Survey, Bull. 856, p. 28–30, 42–62, Pl. 6, col. 1, 16.
322. Thomas, C. R., and others (1944) *Structure contour map of the exposed rocks in the Rangely anticline, Rio Blanco and Moffat counties, Colorado*, U. S. Geol. Survey, Oil and Gas Invest., Prelim. Map 7.
323. —— — —— (1945a) *Mesozoic and Paleozoic stratigraphy in northwestern Colorado and northeastern Utah*, U. S. Geol. Survey, Oil and Gas Invest., Prelim. Chart 16.
324. —— — —— (1945b) *Structure contour map of the Rangely anticline, Rio Blanco and Moffat Counties, Colorado*, U. S. Geol. Survey, Oil and Gas Invest., Prelim. Map 41.
325. Thomas, H. D. (1936) *Frontier-Niobrara contact in Laramie Basin, Wyoming*, Am. Assoc. Petrol. Geol., Bull., vol. 20, p. 1189–1197.
326. Thwaites, F. T., and Twenhofel, W. H. (1920–1921) *Windrow formation, an upland gravel formation of the driftless and adjacent areas of the Upper Mississippi Valley*, Geol. Soc. Am., Bull., vol. 31, p. 133; vol. 32, p. 293–311.
327. Todd, J. E. (1903) *Benton formation in eastern South Dakota*, Geol. Soc. Am., Bull., vol. 15, p. 574.
328. —— (1908) *Elk Point quadrangle, South Dakota, Nebraska, Iowa*, U. S. Geol. Survey, Geol. Atlas, Folio 156.
329. Twenhofel, W. H. (1924) *Geology and invertebrate paleontology of the Comanchean and "Dakota" formations of Kansas*, Kans. State Geol. Survey, Bull. 9, p. 12–25, 30–34.
330. Upham, Warren (1888) *Geology of Minnesota*, vol. 2, p. 461.
331. Vanderwilt, J. W. (1937) *Geology and mineral deposits of the Snowmass Mountain area, Gunnison County, Colorado*, U. S. Geol. Survey, Bull. 884, p. 37–40.
332. Veatch, A. C. (1907) *Geography and geology of a portion of southwestern Wyoming*, U. S. Geol. Survey, Prof. Paper 56, p. 103–104.
333. —— (1911) *Coal deposits near Pinedale, Navajo County, Arizona*, U. S. Geol. Survey, Bull. 431, p. 239–242.
334. Waldschmidt, W. A. (1933) *Characteristics of older Cretaceous formations of northeastern Colorado*, Am. Assoc. Petrol. Geol., Bull., vol. 17, p. 411–421.

STANDARD CLASSIFICATION

European Stages	Gulf Coastal Plain	Reference sequence for Western Interior	Suggested zonal indices
Danian ?		Hell Creek form.	Triceratops
Maestrichtian	Navarro group	Fox Hills ss. / Pierre shale / Montana group	Discoscaphites nebrascensis
?		Sandstone m.	Discoscaphites iris
Campanian		Sh. and ss. m.	
		Timber Lake m.	
		Trail City m.	?
		Elk Butte m.	Baculites grandis
		Mobridge m.	Baculites baculus
		Virgin Creek m.	
		Varendrye m.	Baculites compressus
		De Grey mem.	
		Crow Crk. m.	Baculites gregoryensis
		Gregory m.	
		Sharon Springs member	Baculites asperiformis
Santonian	Taylor marl	Eagle sandstone	Scaphites hippocrepis
		Telegraph Creek formation	Desmoscaphites bassleri
Coniacian		Niobrara form. / Smoky Hill chalk member	Desmoscaphites erdmanni
			Cliscoscaphites choteauensis
			Cliscoscaphites varmiformis
			Scaphites depressus
			Scaphites ventricosus
Turonian	Austin chalk	Niobrara form. / Fort Hays ls. m.	Inoceramus deformis
		Carlile sh. / Greenhorn ls. / Blue Hill sh. m.	Scaphites corvensis
			Scaphites nigricollensis
			Prionocyclus wyomingensis
			Scaphites warreni
		Fairport chy m.	Collignoniceras woollgari
		Pfeifer ls. m.	Inoceramus labiatus
		Lelmore chk. m.	Scipionoceras gracile
		Hartland sh. m.	Durneyoceras cf. D. albertsee
		Lincoln ls. m.	Durneyoceras pondi
Cenomanian	Eagle Ford shale / Woodbine formation	Colorado group / Belle Fourche shale	Acanthoceras ? sp. A
			Acanthoceras ? amphibolum
			Calycoceras sp.
Albian	Washita group	Mowry shale	Neogastroplites sp.
		Newcastle ss.	Gastroplites sp.
		Skull Creek shale	Inoceramus comanchecanus
	Fredericksburg group	Fall River ss.	Oxytropidoceras
	Trinity group	Red shale	?
		Draney limestone	Protelliptio douglassi
		Bechler conglomerate	
		Peterson limestone	
Aptian	Nuevo León group	Gannett group / Ephraim conglomerate	
Barremian			?
Hauterivian	Durango group		
Valanginian			
Berriasian			

Upper Cretaceous — Lower Cretaceous — Comanche series — Gulf series — Senonian of many authors, particularly French ? — Neocomian of many authors — Coahuila

Larger Invertebrate Fossils

Ammonoids 1a: Scaphites | Baculites | Others

Inoceramus

Miscellaneous marine

Non-marine

	IDAHO	WYOMING																
	Southeastern part	Central eastern part	Uinta and Lincoln Counties	Cokeville–Afton region	Snider Basin	Gros Ventre region	Yellowstone Park	Rock Springs region	Lander region	Western part of Bighorn Basin	Eastern part of Bighorn Basin	Rawlins region	Hanna–Walcott region	Rock River region	Laramie region	Co... re...
	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	
	Tertiary	Tertiary	Paleocene	Tertiary		Pinyon form.	Eocene (?)	Eocene	Paleocene	Paleocene	Paleocene	Paleocene	Ferris ★ formation	Eocene	Tertiary	Pal...
								Lance formation		Lance formation	Lance formation	Lance formation	Medicine Bow formation ★			La... for...
						Congl. ss. seq. / White ss. seq. / 46		Lewis shale		Meeteetse ★ formation	Meeteetse formation	Lewis shale	Lewis shale	Lewis shale	Lewis shale	Le... sh...
		Unnamed plant-bearing beds				"Lenticular sandstone and shale sequence"	Judith River formation / 46a	Almond ★ formation / Ericson ★ sandstone / Rock ★ Springs form. / Blair ★ form. / Mesaverde group	"Lance form." / 49 / "Lewis shale"	Mesaverde formation	Mesaverde formation	Teapot ss. m. / Sandstone m. / Shale member / Sandstone m. / Marine ss. m. / Nonmarine coal-bearing m. / Marine ss. m.	Marine ss. m. / Nonmarine coal-bearing m. / Pine Ridge ss. member ★	Mesaverde fm.	Mesaverde formation	Te... Mesaverde fm.
					(Fault contact)	"Cody sequence" / Bacon Ridge sandstone ★ / Cody shale	Telegraph Creek form. / Niobrara and Carlile shales	Baxter —37— shale ★	Cody shale	Cody shale	Cody shale	Steele shale ★	Steele shale	Steele shale	Steele shale	Steele shale
			Hilliard sh. / Kemmerer coal ★ / Oyster Ridge ss. m.		Frontier formation	Marine ss. / Nonmarine beds / Marine ss. and sh. / Nonmarine beds	Frontier formation	Frontier sandstone 30	14	14	14	Niobrara formation	Niobrara formation	Niobrara formation	Niobrara formation	Niobrara fm.
				Porcellanites, shales, sandstones, limestones, minor coal beds. Mostly nonmarine.								Carlile shale / Wall Creek ss. m. / 54	Carlile shale / Wall Creek ss. m.	Wall Crk. ss. m. / 14	Carlile shale / Sage Breaks shale memb. / Wall Creek ss. m. / 14	Niobrara fm. of Thomas / Sage Breaks shale member / Wall Crk. ss. m. / 14
		Frontier formation	Frontier formation								Frontier st. / Torchlight ss. m. / Peay ss. mem. ★	Frontier formation	Frontier formation	Frontier formation	Frontier formation	Frontier formation
		Wayan ★ formation	Aspen shale ★	Aspen shale	Aspen shale	Mowry shale	Mowry shale	Mowry shale	Mowry shale	Mowry shale	Mowry shale	Mowry shale	Mowry shale	Mowry shale	Mowry shale	Benton formation of Darton et al.
		Bear River form. / Red shale and sandst. / Upper ss. m. / 40	Bear River ★ formation	Bear River ★ formation	Bear River formation	Thermopolis sh. / 47 / Muddy ss. m.	Thermopolis sh. / 47 / Muddy ss. m.	Thermopolis sh. / 47 / Greybull ss. m. / Muddy ss. member / 47	Thermopolis sh. / 47 / Muddy ss. / 47	Thermopolis sh. / 47 / Muddy ss. / 47	Thermopolis sh. / 47 / Muddy ss. / 32 / Thermopolis sh.	Thermopolis sh. / 47 / Muddy ss. / 47	Thermopolis sh. / 47 / ss. member / 47	Thermopolis sh. / 47 / Muddy ss. / 47	Thermopolis sh. / 47 / Muddy ss. / 47	Thermo... / Muddy ss. / 47
		Unnamed red shale / 41	Draney ★ limestone / Bechler ★ conglomerate / 41 / Peterson ★ limestone	Draney limestone / Bechler shale / 41 / Peterson limestone	Sandstones and shales equivalent to the upper parts of the Gannett group, plus, at some places, the Bear River formation	Dark shales, marlingtonid beds and limestone members / Marlingtonid beds / ½ / 40 / Red shale / Draney ls. / Bechler shale / Peterson ls.	(interval not well known) / Draney–Peterson limestone	Greybull ss. m. / Shale and sandstone member / Pryor conglomerate member	Sandstone m. / Shale and sandstone member / Conglomeratic sandstone member	Rusty beds / Shale member / Conglomeratic sandstone member	Greybull ss. m. / Shale member / Conglomeratic sandstone member	Greybull ss. m. / Shale member / Conglomeratic sandstone member	Upper ss. mem. / Shale member / Conglomeratic sandstone member	Upper ss. mem. / Shale member / Conglomeratic sandstone member	Upper ss. mem. / Shale member / Conglomeratic sandstone member	Upper ss. mem. / Buff and purple shale member / Conglomeratic sandstone member	Upper ss. mem. / Shale member / Conglomeratic sandstone member
		Lower member / 48	Cloverly formation	Cloverly formation	Cloverly formation	Rusty beds / Lower member / 48	Cloverly formation	Cloverly formation	Cloverly formation	Cloverly formation	Cloverly formation	Cloverly formation	Cloverly formation	Cloverly formation	Cloverly formation	Cloverly formation
		Ephraim conglomerate	Gannett group / Ephraim conglomerate	Gannett group / Ephraim conglomerate	Backwith formation / Conglomeratic member equivalent to the Ephraim conglomerate	Gannett group / Ephraim conglomerate	Gannett group / Ephraim conglomerate									
		? / 42	Stump ss.	Stump ss.	Stump ss.	Stump ss.	Stump ss.									
Underlying formation			Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Ju...
References to bibliography			199, 228, 241	103, 198, 275	332	77, 98, 140, 184–186	363	274, 281	29, 41, 181, 182, 183, 236, 294	134, 135, 233	135, 192	75, 94, 370	74	76, 325	67, 69, 171, 325	17, 320, ...

Chart 10 b.- CORRELATION OF THE CRETACEOUS FORMATIONS OF THE WESTERN INTER

By William A. Cobban and John B. Reeside, Jr.

WYOMING

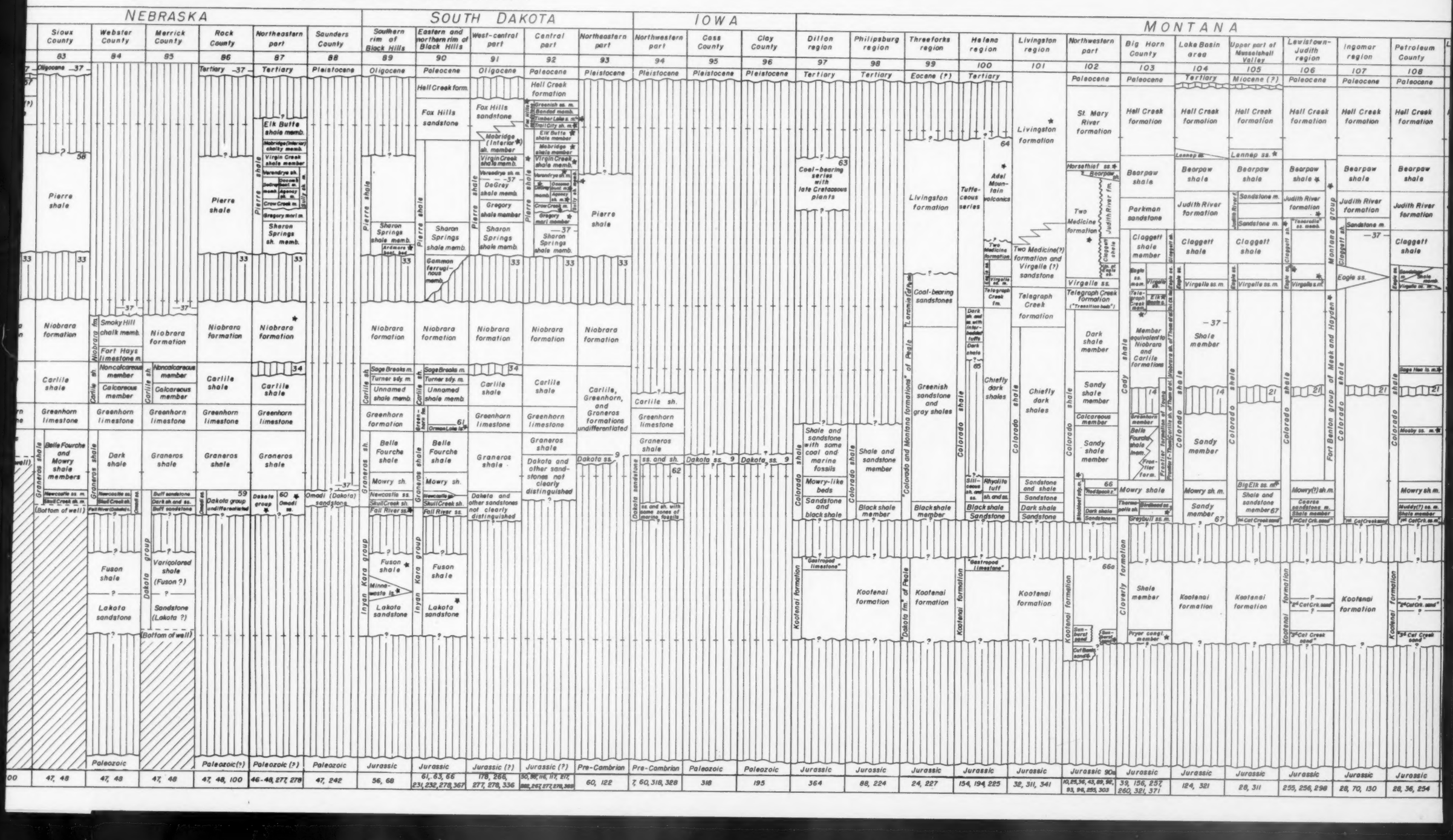
NEBRASKA

SOUTH DAKOTA

Ventre region	Yellowstone Park	Rock Springs region	Lander region	Western part of Bighorn Basin	Eastern part of Bighorn Basin	Rawlins region	Hanna-Walcott region	Rock River region	Laramie region	Casper region	Kaycee-Buffalo region	Southeastern corner	Lance Creek region	Western rim of Black Hills	Banner County	Sioux County	Webster County	Merrick County	Rock County	Northeastern part	Saunders County	Southern rim of Black Hills	Eastern and northern rim of Black Hills	West-central part	Central part	Northeastern part	North
67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	
form.	Eocene (?)	Eocene	Paleocene	Paleocene	Paleocene	Paleocene	Ferris ★ formation	Eocene	Tertiary	Paleocene	Eocene	Oligocene	Paleocene	Paleocene	Oligocene —37—	Oligocene —37—			Tertiary —37—	Tertiary		Oligocene	Paleocene	Oligocene	Paleocene	Pleistocene	Pl
		Lance formation		Lance formation	Lance formation	Lance formation	Medicine Bow formation			Lance formation	Piney ★ formation	Harrington ss. m. ★	Lance ★ formation	Lance formation	Hell Creek 57 formation								Hell Creek form.		Hell Creek formation	
		Lewis shale		Meeteetse ★ formation	Meeteetse formation	Lewis shale	Lewis shale	Lewis shale		Lewis shale		Fox Hills ss.	Fox Hills ss.	Fox Hills ss.	Fox Hills (?) sandstone								Fox Hills sandstone	Fox Hills sandstone	Greenish ss. m. Banded memb. Timber Lake s. m. Trail City sh. m. ★	
		Almond ★ formation				Mesaverde fm. Teapot ss. m. Sandstone m. Shale member Sandstone m.	Mesaverde fm. Marine ss. m. Nonmarine coal-bearing m. Marine ss. m.	Mesaverde fm. Pine Ridge ★ ss. member		Mesaverde fm. Teapot ss. m. ★ Parkman sandstone member Shannon ★ sandstone membr.	Parkman sandstone ★	Bearpaw sh. Parkman ss. Pierre shale	Pierre shale	Monument Hill ★ bentonitic memb. Mitten ★ black shale member Sharon ★ Speer sandstone bed ferruginous member Pedro bent bed	Pierre shale	Pierre shale	Pierre shale	Pierre shale	Pierre shale	Pierre shale	Pierre shale	Elk Butte shale memb. Mobridge (Interior) ★ chalky memb. Virgin Creek shale member Verendrye sh. m. Orman Lake ss. m. Crow Creek m. Gregory marl m. Sharon Springs sh. memb.	Pierre shale	Pierre shale	Elk Butte ★ shale member Mobridge ★ shale member Virgin Creek shale memb. Verendrye sh. m. Orman Lake ss. m. DeGrey shale memb. Gregory shale member Sharon Springs shale memb.	Pierre shale	Pierre shale
		Rock ★ Springs form. Blair form.				Steele shale ★	Steele shale	Steele shale	Steele shale	Steele shale	Pierre shale of Darton Steele shale	Cody shale															
		Baxter —37— shale		Cody shale		Niobrara formation	Niobrara formation	Niobrara formation	Niobrara fm. of Thomas Niobrara fm. of Darton et al.	Niobrara shale	Niobrara formation	Niobrara formation	Niobrara formation	Niobrara formation (Beaver Creek member ★ of Ruby)	Niobrara formation	Niobrara formation	Niobrara formation	Niobrara formation	Niobrara formation	Niobrara formation		Niobrara formation	Niobrara formation	Niobrara formation	Niobrara formation	Niobrara formation	
		Carlile shale				Carlile shale	Carlile shale	Niobrara formation Upper chalky member Upper shale member Lower chalky member Sage Breaks shale memb.		Carlile shale		Apishapa shale member Timpas limestone m.					Smoky Hill chalk memb. Fort Hays limestone m.										
		Frontier sandstone 30		Frontier formation	Frontier formation	Frontier formation Wall Creek ss. m. 54 Wall Creek ss. m.	Frontier formation Wall Creek ss. m. 14	Frontier formation Wall Crk. ss. m. 14 Wall Creek ss. m. 14	Frontier formation	Frontier formation Wall Creek ss. m. 14 Dark shale member containing locally several sandstone members	Colorado shale of Darton	Codell ss. m.	Carlile sh. Sage Breaks shale member Codell (Wall Cr.) ss.	Carlile sh. Sage Breaks shale memb. 56 Turner sdy. m. ★ Unnamed member	Carlile sh. Noncalcareous member Calcareous member	Carlile sh. Noncalcareous member Calcareous member	Carlile shale	Carlile shale	34	Carlile sh. Sage Breaks m. Turner sdy. m. Unnamed shale memb.	Carlile sh. Sage Breaks m. Turner sdy. m. Unnamed shale memb.	Carlile shale	Carlile shale	Carlile, Greenhorn, and Graneros formations undifferentiated	
		Frontier formation									Frontier formation of Darton et al.	Shale with one thin bed of limestone															
				Frontier ss. Torchlight ss. m. ★ Peay ss. mem. ★	Cody shale				Benton formation of Darton et al.		Benton shale of Darton et al. Frontier form.																	
		Mowry shale	Mowry shale	Mowry shale	Mowry shale	Mowry shale	Mowry shale	Mowry shale	Mowry shale	Mowry shale	Mowry shale	Shales equivalent to the Greenhorn and Belle Fourche formations	Greenhorn limestone	Greenhorn limestone	Greenhorn limestone	Greenhorn limestone	Greenhorn limestone	Greenhorn limestone	Greenhorn limestone	Greenhorn limestone	Greenhorn limestone	Greenhorn formation	Greenhorn limestone	Greenhorn limestone	Greenhorn limestone		
		Thermopolis sh. Muddy ss. member 47	Thermopolis sh. Muddy ss. 47	Thermopolis sh. Muddy ss. 47	Thermopolis sh. Muddy ss. 47	Thermopolis sh. Muddy ss. 47	Thermopolis sh. Muddy ss. 47	Thermopolis sh. Muddy ss. 47	Thermopolis sh. Muddy ss. 47	Thermopolis sh. Muddy ss. 47	Mowry shale ★ Thermopolis sh.	Mowry sh. m.	Belle Fourche shale memb.	Belle Fourche ★ shale	Graneros shale	Graneros shale	Graneros shale	Graneros shale	Graneros shale	Graneros shale	Graneros shale	Graneros sh.	Graneros shale	Graneros shale	Graneros shale	Dakota and other sandstones not clearly distinguished		
		Greybull ss. m. 47	Greybull ss. m. 53	Greybull ss. m. 52								Sandstone mem.	Greenhorn limestone	Mowry shale Hartzog ss. (Sh. Ck.) Skull Crk. sh. Greybull ss. m. of Cobban	Bottom of well)	Bottom of well)	Newcastle ss. m. Skull Creek sh. m. Fall River (Dakota) s.	Newcastle ss. Skull Creek sh. Fall River (Dakota) ss.	Newcastle ss. Skull Creek sh. Fall River ss.	Newcastle ss. Skull Creek sh. Fall River ss.	Newcastle ss. Skull Creek sh. Fall River ss.	Newcastle ss. Skull Creek sh. Fall River ss.	Newcastle ss. Skull Creek sh. Fall River ss.	Newcastle ss. Skull Creek sh. Fall River ss.	Dakota and other sandstones not clearly distinguished	Dakota ss.	
		Shale and sandstone member	Shale member	Shale member	Shale member	Shale member	Shale member	Shale member	Buff and purple shale member	Shale member	Cloverly formation	Shale member	Fall River ss.	Fall River ss.													
		Pryor conglomeratic member	Conglomeratic sandstone member	Conglomeratic sandstone member	Conglomeratic sandstone member	Conglomeratic sandstone member	Conglomeratic sandstone member	Conglomeratic sandstone member	Conglomeratic sandstone member	Conglomeratic sandstone member		Sandstone member	Inyan Kara group Lakota sandstone	Inyan Kara group Fuson ★ shale Lakota sandstone													
Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Paleozoic		Paleozoic		Paleozoic(?)	Paleozoic (?)	Paleozoic	Jurassic	Jurassic	Jurassic (?)	Jurassic (?)	Pre-Cambrian	Pre-
98, 184-186	363	274, 281	29, 41, 181, 182, 183, 236, 294	134, 135, 233	135, 192	75, 94, 370	74	76, 325	67, 69, 171, 325	17, 127, 128, 320, 342, 343, 346	59	69, 171, 269	79, 87, 125, 158	52, 72, 264	48, 100	47, 48	47, 48	47, 48	47, 48, 100	46-48, 277, 279	47, 242	56, 68	61, 63, 66 231, 232, 278, 367	178, 266, 277, 278, 336	50, 187, 116, 117, 277, 278, 365	60, 122	? 60

OF THE CRETACEOUS FORMATIONS OF THE WESTERN INTERIOR OF THE UNITED STATES (Continued)

By William A. Cobban and John B. Reeside, Jr.



Prepared under the auspices of the Committee on Stratigraphy of the National Research Council, Carl O. Dunbar, *Chairman*

MONTANA

NORTH DAKOTA

MINNESOTA

WIS.

g Horn County	Lake Basin area	Upper part of Musselshell Valley	Lewistown–Judith region	Ingomar region	Petroleum County	Little Rocky Mountain region	Cedar Creek anticline	Fort Peck region	Williams County	Bismarck region	Ward County	Foster County	Pembina Escarpment, Manitoba and North Dakota	Junction of Red and Pembina Rivers	Lyon County	Brown County	Nicollet County	Fillmore County	Lac Qui Parle County	Stearns County	Clay County	Wadena County	Roseau County	Mesabi Range	Monroe County
103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128
Paleocene	Tertiary	Miocene (?)	Paleocene	Paleocene	Paleocene	Paleocene	Paleocene	Paleocene	Paleocene –37–	Paleocene –37–	Paleocene –37–	Tertiary (?)	Paleocene	Pleistocene	Pleistocene	Pleistocene	Pleistocene	Pleistocene	Pleistocene	Pleistocene	Pleistocene	Pleistocene	Pleistocene	Pleistocene	Pleistocene
...off Creek formation	Hell Creek formation	Hell Creek formation	Hell Creek formation	Hell Creek formation	Hell Creek formation	Hell Creek formation	Hell Creek formation	Hell Creek formation ★	Hell Creek formation	Hell Creek fm. / Marine member / Fox Hills sandstone	Hell Creek formation / Fox Hills sandstone	?	? Boissevain formation	?											
	Lennep ss.	Lennep ss. ★						Pas. white ss. / Colgate s.m.																	
...earpaw shale	Bearpaw shale	Bearpaw shale	Bearpaw shale ★	Bearpaw shale	Bearpaw shale	Bearpaw shale		Fox Hills sandstone / Bearpaw shale																	
...Parkman sandstone	Judith River formation	Judith River / Sandstone m. / Sandstone m. ★	Judith River formation ★ / "Fosterella" ss. mem.	Judith River formation / Sandstone m.	Judith River formation	Judith River formation	–37–	Judith River formation	Pierre shale	Pierre shale	Pierre shale	Pierre shale –37–	Riding Mountain formation, including Odanah facies	? Divisions C, D, and E of Berkey											
...Claggett shale member	Claggett shale	Claggett shale	Claggett sh. / Virgelle ss. m. / Virgelle s.m.	Claggett sh. / Eagle ss.	Claggett shale	Claggett shale	"Judith River sand" of drillers	Claggett shale					Pembina member												
Eagle ss. member / Telegraph Creek form. / Virgelle ss. / Eagle ss. / Virgelle ss. / Eagle ss. / Virgelle ss.	Virgelle ss. m.	Virgelle ss. m.	Virgelle s.m.	Eagle ss.	Sandstone member / Shale member / Virgelle ss. m.	Eagle ss. / Shale member / Virgelle ss. m.	"Eagle ss." of drillers	Eagle (?) ss.																	
Member equivalent to Niobrara and Carlile formations	–37– Shale member								Niobrara formation	Niobrara formation	Niobrara formation	Niobrara and Benton formations undifferentiated	Vermilion River formation / Boyne member / ? Morden member / Favel form. / Assiniboine member / Kaid member	? Division B of Berkey											
14 / Greenhorn member / Belle Fourche shale mem. / Frontier formation / Carlile sh. of Thom etc. / Niobrara sh. of Thom etc. / Frontier formation of Young / Carlile sh. of Thom etc. / Niobrara sh. of Thom etc.	14 Sandy member	21	21	21	21	21	Greenhorn limestone		Benton formation	Benton formation	Carlile formation / Greenhorn formation / Graneros formation		Ashville formation	? Division A of Berkey	? Dark shale / ? Greenish sand / ? Blue shale	?	?	? –37–	?	?	?	?	?	?	?
Colorado shale / Fort Benton group of Meek and Hayden / Colorado shale / Colorado shale / Colorado shale / Colorado group / Graneros shale / Colorado shale							Belle Fourche shale member / Mowry sh. m. / Newcastle s.m. / Skull Ck. sh. m.																		
Mowry shale	Mowry sh. m.	Big Elk ss. m.	Mowry(?) sh. m.		Mowry sh. m.	Mowry shale	Mowry (?) sh. meinb.																		
Greybull ss. m.	? 67	Shale and sandstone member 67	Coarse sandstone m. / Shale member	1st Cat Creek sand	Muddy(?) ss. m. / Shale mem. / Sandstone m.	Muddy(?) ss. m. / Shale mem. / Sandstone m.	Fall River ss.		Dakota and probably other ss. not clearly distinguished	Dakota and probably other ss. not clearly distinguished (Bottom of well)	Dakota and probably other ss. not clearly distinguished	Dakota and probably other ss. not clearly distinguished													
Cloverly formation / Shale member / Pryor congl. member ★	Kootenai formation	Kootenai formation	Kootenai formation / 2nd Cat Crk. sand / 2nd Cat Creek sand	Kootenai formation	Kootenai formation / 2nd Cat Crk. sand / 2nd Cat Creek sand	Kootenai formation / Arkosic ss.	Inyan Kara group / Fuson shale / Lakota ss.	Kootenai formation					Swan River formation												
Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic (?)		Jurassic	Paleozoic	Jurassic	Paleozoic	Pre-Cambrian	Pre-Cambrian	Paleozoic	Paleozoic	Pre-Cambrian	Pre-Cambrian	Pre-Cambrian	Pre-Cambrian	Pre-Cambrian	Pre-Cambrian	Paleozoic
39, 156, 257, 260, 321, 371	124, 321	28, 311	255, 256, 298	28, 70, 130	28, 36, 254	44, 157, 253	16, 73, 91	18, 42, 149, 286	159, 160	82, 159, 161, 175, 179	159, 319	159, 248	153, 210, 359, 361	11, 22	60, 122, 365	122	122, 268	300, 301	122, 127	122, 156, 330	4	4	4	21, 121, 173, 300	326

Big Coffeeville fm. of Sardeson ★ — Dalrander memb. of Dakota fm. ★ — Graneros(?)sh. — Dakota ss. — Benton formation — Graneros(?) sh. — Dakota ss. — Coleraine formation ★ — Windrow formation ★ — 68

335. W

336. W

337. —

338. W

339. —

340. W

341. W

342. W

343. —

344. —

345. —

346. —

347. W

348. W

349. —

350. —

351. —

352. —

353. —

354. —

355. —

356. —

335. Walton, P. T. (1944) *Geology of the Cretaceous of the Uinta Basin, Utah*, Geol. Soc. Am., Bull., vol. 55, p. 91–130.
336. Ward, Freeman (1925) *Structures in northern Haakon County*, S. D. Geol. Nat. Hist. Survey, Circ. 22.
337. —— (1926) *The position of the Interior formation*, Am. Jour. Sci., ser. 5, vol. 11, p. 350–352.
338. Warren, P. S. (1930) *New species of fossils from Smoky River and Dunvegan formations, Alberta*, Alberta Res. Council, Geol. Survey, Rept. 21, p. 57–68.
339. —— and Stelck, C. R. (1940) *Cenomanian and Turonian faunas in the Pouce Coupe District, Alberta and British Columbia*, Roy. Soc. Canada, Tr., ser. 3, vol. 34, sec. 4, p. 143–152.
340. Washburne, C. W. (1910) *The South Park coal field, Colorado*, U. S. Geol. Survey, Bull. 381, p. 307–308.
341. Weed, W. H. (1894) *Livingston quadrangle, Montana*, U. S. Geol. Survey, Geol. Atlas, Folio 1.
342. Wegemann, C. H. (1911) *The Salt Creek oil field, Wyoming*, U. S. Geol. Survey, Bull. 452, p. 42–54.
343. —— (1912) *The Powder River oil field, Wyoming*, U. S. Geol. Survey, Bull. 471, p. 60–68.
344. —— (1914) *Geology and coal resources of the Sierra Blanca coal field, Lincoln and Otero counties, New Mexico*, U. S. Geol. Survey, Bull. 541, p. 430–431.
345. —— (1915) *The Coalville coal field, Utah*, U. S. Geol. Survey, Bull. 581, p. 163.
346. —— (1918) *The Salt Creek oil field, Wyoming*, U. S. Geol. Survey, Bull. 670, p. 12–24.
347. Weller, Stuart (1907) *Cretaceous paleontology of New Jersey*, N. J. Geol. Survey, Paleont., vol. 4, 871 pages.
348. White, C. A. (1878) *Report on the geology of a portion of northwestern Colorado*, U. S. Geol. Geog. Survey Terr., 10th Ann. Rept., p. 21, 22, 30.
349. —— (1879a) *Contributions to invertebrate paleontology, no. 1: Cretaceous fossils of the western States and Territories*, U. S. Geol. Geog. Survey Terr., 11th Ann. Rept. p. 273–319.
350. —— (1879b) *Report on the paleontological field work for the season of 1877*, U. S. Geol. Geog. Survey Terr., 11th Ann. Rept. p. 161–272.
351. —— (1880) *Note on* Criocardium *and* Ethmocardium, U. S. Nat. Mus., Pr., vol. 2, pt. 2, p. 291.
352. —— (1883a) *Contributions to invertebrate paleontology, no. 4: Fossils of the Laramie group*, U. S. Geol. Geog. Survey Terr., 12th Ann. Rept., pt. 1, p. 49–103.
353. —— (1883b) *A review of the nonmarine fossil Mollusca of North America*, U. S. Geol. Survey, 3d Ann. Rept., p. 409–479.
354. —— (1884) *A review of the fossil Ostreidae of North America*, U. S. Geol. Survey, 4th Ann. Rept., p. 273–430.
355. —— (1891) *Correlation papers: Cretaceous*, U. S. Geol. Survey, Bull. 82.
356. —— (1895) *The Bear River formation and its characteristic fauna*, U. S. Geol. Survey, Bull. 128, 108 pages.
357. Whitfield, R. P. (1880) *Paleontology of the Black Hills of Dakota*, in Newton, Henry, and Jenney, W. P.: *Report on the geology and resources of the Black Hills of Dakota*, U. S. Geog. Geol. Survey Rocky Mtn. Reg., p. 329–470.
358. —— (1907) *Remarks on and descriptions of new fossil Unionidae from the Laramie clays of Montana*, Am. Mus. Nat. Hist., Bull., vol. 23, p. 627.
359. Wickenden, R. T. D. (1931) *Variation in thickness of Cretaceous formations in southern Manitoba*, Geol. Survey Canada, Summ. Rept. 1930, pt. B, p. 72–73.
360. —— (1932) *Notes on some deep wells in Saskatchewan*, Roy. Soc. Canada, Tr., ser. 3, vol. 26, sec. 4, p. 179–181.
361. —— (1945) *Mesozoic stratigraphy of the eastern plains, Manitoba and Saskatchewan*, Geol. Survey Canada, Mem. 239, p. 7–51.
362. Wilmarth, M. G. (1938) *Lexicon of geologic names of the United States (including Alaska)*, U. S. Geol. Survey, Bull. 896, 2396 pages.
363. Wilson, C. W., Jr. (1934) *Section of Paleozoic and Mesozoic rocks measured at Cinnabar Mountain, Park County, Montana, and at Mount Everts, Yellowstone National Park, Wyoming*, Am. Assoc. Petrol. Geol., Bull., vol. 18, 368–379.
364. Winchell, A. N. (1914) *Mining districts of the Dillon quadrangle, Montana, and adjacent areas*, U. S. Geol. Survey, Bull. 574, p. 23, 25.
365. Winchell, N. H. (1886) *Notes on some deep wells in Minnesota*, Minn. Geol. Nat. Hist. Survey, 14th Ann. Rept., p. 351–353.
366. Winchester, D. C. (1920) *Geology of Alamosa Creek Valley, Socorro County, New Mexico*, U. S. Geol. Survey, Bull. 716, p. 5–10.
367. —— and others (1916) *The lignite field of northwestern South Dakota*, U. S. Geol. Survey, Bull. 627, p. 15–26.
368. Wing, M. E. (1940) *Bentonites of the Belle Fourche district*, S. D. Geol. Survey, Rept. Invest. 35.
369. —— and Gries, J. P. (1941) *Stratigraphy and structure of the Chamberlain section of the Missouri Valley*, S. D. Geol. Survey, Rept. Invest. 39.
370. Wyoming Geological Association (1951) *Guidebook 6th Annual Field Conference, South Central Wyoming*, Casper, Wyoming.
371. Young, Keith (1951) *Foraminifera and stratigraphy of the Frontier formation (Upper Cretaceous), southern Montana*, Jour. Paleont., vol. 25, p. 35–48.
372. Zapp, A. D. (1949) *Geology and coal resources of the Durango area, La Plata and Montezuma counties, Colorado*, U. S. Geol. Survey, Oil and Gas Invest., Prelim. Map 109.

U. S. Geological Survey, Washington, D. C.
Manuscript Received by the Secretary of the Society, March 24, 1952.
Publication Authorized by the Director, U. S. Geological Survey.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 63, PP. 1045-1052 OCTOBER 1952

METHOD FOR DETERMINING THE AGE OF IGNEOUS ROCKS USING THE ACCESSORY MINERALS

BY E. S. LARSEN, JR., N. B. KEEVIL, AND H. C. HARRISON

ABSTRACT

The age of igneous rocks is determinable by a method based on the included accessory minerals. In the common igneous rocks, most of the lead is concentrated in the potassium minerals, and most of the radioactivity is in the zircon and other accessory minerals. The lead in the potassium minerals is believed to be mostly primary lead; that in zircon is probably chiefly radiogenic lead. By separating the zircon of fresh igneous rocks, determining the amount of lead with the spectrograph and the radioactivity by alpha counters, the age of Paleozoic and Precambrian rocks can be determined with an accuracy of approximately 90 per cent. Basalts and gabbros may contain too few accessory minerals for satisfactory age determination by this method. Zircon is the most satisfactory mineral for this kind of determination. Apatite and sphene give high results and therefore must contain primary lead. Sphene gives erratic results.

CONTENTS

TEXT

	Page
Introduction and acknowledgments	1045
Contamination of mineral samples	1047
Preparation of mineral samples	1047
Calculation of age	1048
Age determinations	1049
Conclusions	1051
Time and equipment required	1052
References cited	1052

TABLES

Table	Page
1. Distribution of PbO, K_2O, and radioactivity in minerals of a typical quartz diorite from the Cretaceous batholith of southern California	1046
2. Average value of $\frac{U}{eU}$ and of c for the chief accessory minerals of igneous rocks	1049
3. Data on age determinations of minerals	1052

INTRODUCTION AND ACKNOWLEDGMENTS

The method described here for the determination of the age of any fresh igneous rock by examination of the included accessory minerals is an outgrowth of a study of the systematic distribution of the rare elements in the rocks of petrographic provinces and in the minerals of these rocks. In the typical quartz diorite from the batholith of southern California (Larsen and Keevil, 1942, p. 209; 1947), the PbO, K_2O, and radioactivity are distributed in the minerals of the rocks as shown in Table 1. The proportions of the accessory minerals in the rocks were determined by heavy-liquid separations and are only approximate.

Because the ionic radii of potassium and lead are almost equal (1.33 and 1.32 A), lead tends to concentrate in the potassium minerals. Most of the lead in these potassium minerals and in the other major constituents must be primary, i.e., crystallized with the mineral during the cooling of the magma. For example, more than 99 per cent of the lead in microperthite of a granodiorite must be primary lead.

The radioactivity is concentrated in the accessory minerals, especially the zircon, monazite, and allanite.

The great difference in ionic radii of zirconium (0.82 A) and lead (1.32 A) and the close packing of zircon would leave little chance for primary lead to invade the zircon. Determinations of lead and radioactivity in zircons from Miocene rocks partly confirm this expectation. Accepting this as true, it should be possible to determine the age of a zircon by determining

the radioactivity and the lead in the mineral. In fresh igneous rocks, the zircon seems to be well protected from alteration processes that would introduce or remove radioactive material

TABLE 1.—DISTRIBUTION OF PbO, K_2O, AND RADIOACTIVITY IN THE MINERALS OF A TYPICAL QUARTZ DIORITE FROM THE CRETACEOUS BATHOLITH OF SOUTHERN CALIFORNIA

	Per cent in rock	PbO	Radioactivity	K_2O
		ppm.	*α/mg/hr*	
Rock	100	18	0.9	1.5
Quartz	20	5	0.2	0.0
Plagioclase	49	15	0.3	0.6
Biotite	18	32	0.4	8.3
Hornblende	13	12	0.8	0.8
Apatite	0.2	5+	56.	0.0
Zircon	0.02	40	400.	0.0
Magnetite	0.1		0.6	0.0
Sphene	0.04	36	260.	0.0
Allanite	Trace		3600.	0.0
Monazite	Trace		4000.	0.0

or lead. Such zircon is high in radioactivity and hence should be high in radiogenic lead. Allanite, monazite, and some other minerals may also be as favorable as zircon for such age determinations. Apatite and sphene seem to be less favorable, but worth testing.

We therefore investigated the possibility of determining the age of rocks by this method, using the spectrograph to determine the lead and using alpha counters to determine the radioactivity. The method was tried on rocks of known age to see how closely the determined age agreed with the known age. This method may have some theoretical disadvantages, but it avoids many uncertain sources of error that beset the geological method. There are probably compensating errors, and the resulting age determination will be very useful to geologists if, for instance, we could say that 9 times out of 10 the age is $x \pm y$ million years.

A mineral to be usable for determining the age of rocks by this method should have only radiogenic lead, should have lost no lead, should have only primary radioactive elements, and should have lost none of them.

It is impossible to make perfect separations of minerals, but nearly all of our separates were 99+ per cent pure. An age determination based on a mixture of two minerals from a granite, either of which would have yielded a good age determination, should itself be good. An illustration of this is a rock containing zircon and uraninite. Some zircon concentrates contain a few black grains or cubes that may be uraninite. The mixture should yield a good age determination. On the other hand, an impurity that contains primary or introduced lead would yield too great an age.

It is a common practice in age determinations to correct the lead determinations for primary and introduced lead by determining the isotopes of lead. By ordinary methods, determination of the isotopes requires from 1 to 12 mg. of lead. Zircon from a Cretaceous granite (L 2) contains approximately 40 ppm of lead, and hence 100 g of zircon would be required to yield 4 mg of lead. The average granite contains about 0.02 per cent of zircon. It would be necessary to separate the zircon from about half a ton of granite and recover the lead from the resulting 100 g of zircon to get 4 mg of lead.

In testing age determinations on rocks of known age, we used several minerals from the same rock and several rocks from the same batholith to give as many checks as possible. To estimate the amount of primary lead in zircon or other minerals, we selected some very young rocks, because a given amount of primary lead in a young mineral would make a much larger relative error in the age determination than it would in an older mineral. A few minerals tested were used because large samples were available.

We believe that the method is practicable for the determination of the age of almost any fresh igneous rock or group of rocks and that its cost can be moderate. We aim for an accuracy of 90 per cent in the age, but the tests so far have not accomplished this for young rocks. Further work is in progress.

Most of the work for this research was done at the Department of Mineralogy, Harvard University, and at the Department of Physics, University of Toronto. The project was financed by the Penrose Bequest of The Geological Society of America. Larsen is responsible for the geology and for separating the minerals. He was ably supported by Mrs. Ursula Chaisson and Miss Roslyn Pill. Keevil carried out

the radiographic part of the project, assisted by Dr. F. E. Senftle. Harrison, assisted by Dr. Robert Allen, did the spectrographic work. Several of the lead determinations were made or checked by Mr. C. L. Waring of the Trace Elements Section, Geochemistry and Petrology Branch of the U. S. Geological Survey.

Contamination of Mineral Samples

In preparing the minerals in minute amounts, it was necessary to use the utmost care to avoid contamination. A sample of 1 kg of granodiorite will yield about 100 mg of zircon, and this zircon will contain about 0.0005–0.05 mg of radiogenic lead, whereas apatite contains only about a twentieth as much radiogenic lead.

All the samples were prepared in a room used only for this work and with equipment—grinding and separating—used only for these samples. New glassware was used. Grinding equipment was first carefully cleaned; after a sample of granite was ground, the equipment was again cleaned. This grinding and cleaning process was repeated several times before the test samples were ground. The machines were then used only for this work. Contamination of one sample of granite by another is not serious if usual care is taken, but no lead minerals or radioactive minerals were allowed in the room. Bolting-cloth screens attached to clean paper cartons were used; ordinary metal screens were avoided. Steel instruments were used; they contain little lead, and fragments of steel could be removed easily in the later preparation of the samples. The heavy liquids were new when first used, and none of them was used for samples other than the powders of granite. The heavy liquids and the acetone used for washing were tested by spectrographic methods and found to have no determinable lead.

Preparation of Mineral Samples

The amount of the accessory minerals in the average granite is commonly very small. Gabbros rarely contain more than traces of zircon, but many contain apatite and sphene. Quartz diorites and granodiorites contain the largest amounts of the accessory minerals; potassium-rich granites contain very little.

The procedure varied but commonly was about as follows:

A large thin section of the rock with an area of about 500 sq. mm was carefully examined and the areas occupied by zircon on the upper surface of the rock section were estimated. The sum of these areas divided by the area of the section gives the percentage by volume of the zircon in the thin section. Some of the sections were very poor samples of the rock. For example, a thin section of a granodiorite from Idaho had a single crystal of allanite that had an area of more than a square millimeter, indicating more than 0.2 per cent of allanite. A separation of the rock yielded only 0.01 per cent of allanite. Probably, on an average, only one slide in 20 would have shown such a large allanite crystal. The estimated relative proportion of the mineral to be separated determined the amount of powdered rock to be used in the separation. Usually a kilogram or more was used.

The rock samples were ground in a laboratory jaw crusher and a disk grinder or roll to 20 or 40 mesh. These powders were sized to 40–60, 60–100, 100–200, and minus 200 mesh. Such minerals as zircon and apatite break out of their matrix and usually are present as well-formed crystals, so they are much concentrated in the rather fine sizes, depending on the size of the crystals in the rock. When ample rock powder was available, the coarser part—usually coarser than 60 mesh—and the part finer than 200 mesh were discarded without much loss of zircon and apatite. This reduced the sample treated in heavy liquids by about half.

The two sizes, 60–100 and 100–200 mesh, were run through bromoform. Large separatory funnels can be used for this separation. The opening in the stopcock of the funnel must be large enough to allow the largest grains to pass through easily without packing of the grains. Beakers can be used and they are more rapid than separatory funnels. For large samples, 40–100 mesh, we used a 4-liter beaker, filled it two-thirds full of bromoform (sp. gr. above 2.8), added about 300 g of powdered rock, stirred with a large stainless-steel kitchen spoon, and allowed to settle. The float was then dipped out into a second beaker partly filled with bromoform and allowed to settle a second time. The float from this second beaker was dipped out and filtered in a 151-mm Buchner funnel under suction. The part of the float

that could not be removed easily with the spoon was poured onto the filter. More powder and heavy liquid were passed through the two beakers until the whole sample was separated. The heavy part was stirred, allowed to settle, and the light part decanted. The final cleaning was done in a separatory funnel. The resulting heavy-mineral sample, which should contain the accessory minerals and the mafic minerals, is usually 5–20 per cent of the original sample. This procedure can be used on material as fine as 200 mesh.

The heavies were next separated roughly into fractions with the Frantz Isodynamic separator. Usually the following fractions were separated: (1) The magnetic fraction obtained with a strong horseshoe magnet consisted chiefly of magnetite; (2) The magnetic fraction with the Frantz set at 2 amp. consisted of ilmenite with some biotite and hornblende; (3) The magnetic fraction with the Frantz set at 4 amp. consisted of biotite, hornblende, allanite, and pyroxene; (4) The magnetic fraction with the Frantz set at 5 or 6 amp. consisted chiefly of monazite; (5) The magnetic fraction with the Frantz set at 14 amp. consisted chiefly of sphene; (6) The nonmagnetic fraction remaining was made up of zircon, apatite, fluorite, pyrite, molybdenite, feldspar, and quartz.

The nonmagnetic fraction was separated in methylene iodide, and the heavies were chiefly zircon and sulfides. This fraction usually contains some sphene which can be removed with the electromagnet. Thus a sample containing 99 per cent of zircon can be recovered and this can be further cleaned by hand picking. Pyrite when heated for a few minutes to 450°C becomes strongly magnetic and can then be removed with the horseshoe magnet.

The apatite and fluorite, with some quartz and feldspar, are now in the nonmagnetic part of the sample and have a specific gravity less than that of methylene iodide and greater than that of bromoform. It can be cleaned with bromoform and an electromagnet. Usually a sample of apatite 99 per cent pure can be obtained, but fluorite has about the same specific gravity as apatite and is difficult to separate. One per cent of perthite in the apatite concentrate might add nearly 1 ppm of lead to the sample, and, for a very young rock, this might be greater than the quantity of radiogenic lead in the apatite.

In all stages of the separations, the samples were examined in immersion liquids under the microscope to determine the next step. Care, patience, and some ingenuity are required. If necessary, the minerals in the oil immersions can be recovered by washing on a filter with acetone.

Allanite is rather difficult to remove. It has about the same magnetism as biotite and hornblende at about 4 amp. on the Frantz separator, and all three minerals are nearly opaque in grains and look much alike. Xenotime can be separated at about 4 amp. Allanite may be concentrated with the magnet and cleaned even from epidote by passing through methylene iodide or a solution of iodoform in methylene iodide (sp. gr. 3.43). This solution is nearly opaque, but it is otherwise nearly as satisfactory as methylene iodide. It can be washed out of the sample readily with acetone.

Clerici solution was avoided because it may contain lead.

Bromoform was found a more satisfactory heavy liquid than acetylene tetrabromide. It is much less viscous and hence grains will settle more rapidly, and it is much easier to filter. A very fast filter paper was usd.

The separates from bromoform, acetylene tetrabromide, or methylene iodide were washed with acetone (technical) and the washings put in large flasks more than half filled with water. The heavy liquid settles to the bottom, and the acetone dissolves in the water. Repeated washing of the settled heavy liquid with tap water is necessary. When a large amount of sand has been wet with heavy liquid, it is difficult to wash the sand on a filter. The sand was washed into a large beaker with acetone, the acetone decanted, more acetone added, and the sand again washed.

A separation about the same as that accomplished with bromoform was made rapidly by flotation, probably the quickest and most practical method.

Calculation of Age

The approximate formula for calculating the age is:

$$T = \frac{c\ Pb}{\alpha}$$

where T is the age in millions of years (MY), Pb is the radiogenic lead in parts per million (ppm), α is the radioactivity (α/mg/hr), and c is a constant that varies with the proportion of uranium and thorium. This constant is 2680 for uranium alone, 1980 for thorium alone, and 2325 for the approximate average proportions of uranium and thorium in rocks. Using this average value for c may introduce an error as large as 17 per cent in the age, which will be too low if uranium alone is present and too high if thorium alone is present.

To find a more accurate value for c for the minerals, Miss Mary Fletcher of the U. S. Geological Survey kindly determined the uranium content of several samples of zircon, apatite, and sphene. The values of alpha for these samples were also known; from these data and from the literature, rough average values of c were determined for the chief accessory minerals of igneous rocks (Table 2).

Table 2.—Average Value of $\frac{U}{eU}$ and of c for the Chief Accessory Minerals of Igneous Rocks*

	$\frac{100\ U}{eU}$	c
Zircon	71	2480
Apatite	27	2180
Sphene	67	2453

*U = amount of uranium present; eU = amount of uranium required to yield the same number of alpha particles as the sample.

Age Determinations

Eight groups of rocks ranging in age from Precambrian to late Miocene were tested by the method proposed in this paper. Work on the younger rocks should test the method most rigorously. Some of the minerals were used because abundant pure material was available for testing methods. The ages of all the formations were known at least approximately. The data are preliminary and some further checks are necessary, especially of the determinations of lead and the purity of the samples. The data, listed in Table 3, are arranged in approximate order of decreasing age. The ages in the column headed "From geology" are taken from Holmes (1947, p. 145) and Simpson (1949, p. 12) and are only approximate.

1. Renfrew, Canada: Large crystals of zircon, sphene, and apatite from the stockroom of the Department of Mineralogy of Harvard University. They were intended chiefly to test methods for the determination of lead. Their age is reported to be about 1000 million years. The samples tested were free from sulfides and other impurities. The age determinations of zircon and apatite check well with the known age, but those of sphene were low.

2. Wichita Mountains, Oklahoma: Zoned zircon crystals which (Dr. Robert H. Dott, personal communication), "came from a pegmatite that intrudes all other igneous rocks of the area and hence appears to represent the youngest pre-Cambrian of the region." The crystals are stubby with steep pyramids and short prisms; some are more than a centimeter across. A thin section shows broad alternating zones of ordinary birefracting zircon and metamict zircon. The contact of the two types is sharp and is a crystal face. The zoning resembles recurrent zoning in plagioclase. The ordinary zircon is uniaxial (+); $\omega = 1.918$, $\epsilon = 1.971$. The metamict mineral is chiefly isotropic, $n = 1.820$; a little of the metamict mineral is weakly birefracting and has n as high as 1.86. The fresh and metamict parts can be separated with an electromagnet or by breaking out the grains of fresh zircon with a needle. The fresh zircon is fractured; the metamict part is little fractured. The samples used were free from impurities. The ordinary zircon is less radioactive than most zircons from granitic rocks and is about as active as zircons from pegmatites. The metamict part has about the activity of zircons for ordinary granitic rocks. The age calculated for the four samples is much the same and averages 706 million years, which is consistent with a late Precambrian age.

3. Statesville, North Carolina: Large zircon crystals from the Harvard collections, believed to be about Devonian. Two samples of the crystals were tested. They were free from impurities.

TABLE 3.—DATA ON AGE DETERMINATIONS OF MINERALS

Source and number of sample	I	Lead (ppm)				Age (MY)		Quality*
		Harrison	Allen	Waring	Average	Calculated	From Geology	
	a/mg/hr							
1. Renfrew, Canada								
Z_4 Zircon	84	32	25	27, 33	30	900	Precambrian 1000	Good
P_M Apatite	35.7		10	17, 18	17½	1070		Good
S_7 Sphene	260	55	49	17, 23	41	490		Poor
S_1 Sphene	122	43	30		36	630		Poor
2. Oklahoma zircon								
Z_1 98% fresh	326	94	87	87	88	675	Late Precambrian 700	Good
Z_2 95% metamict	970	282	295		288	742		Good
Z_3 97% fresh	135	40	45	39	40	741±		Good
Z_4 90% metamict	1203	330	350	338	340	688		Good
Weighted average						706		
3. Statesville, North Carolina								
Z_5 Zircon	400	51	47	49	49	306	Devonian 300±	Good
Z_{13} Zircon	239	31	36		33	345		Good
Weighted average						325		
4. New Hampshire White Mountain magma series								
Z_{11} Conway quarry zircon	1184	126	106	127, 121, 130	127	268	Carboniferous 250	Good
5. Vermont								
S_{12} Sphene	107	14		12	13	300	Devonian 300±	Good
6. Batholith of Southern California								
Z_7 El 134 Zircon	752	28	27	35	30	100	Cretaceous (middle) 100±	Good
S_1 Sphene, Valverde	162	62	60	67	63	920		Very poor
S_8 Sphene, Valverde	241		28	12, 11	12 (?)	128		Fair
P_4 El 134 Apatite	200	8	1½	18, 20	19	200		Very poor
P_6 El 134 Apatite	77.4	14	7		10	280		Very poor
P_3 SLR 299 Gabbro Apatite	9.6			62, 63	62	?		Very poor
7. Snoqualmie batholith, Washington								
Z_6 Zircon	794	9	17	16, 21, 23	16	63	Miocene 25	Poor
P_7 Apatite	22	0.2	2	8, 7, 6	7	700		Very poor

TABLE 3.—*Continued*

Source and number of sample	I	Lead (ppm)				Age (MY)		Quality*
		Harrison	Allen	Waring	Average	Calculated	From Geology	
	$\alpha/mg/hr$							
8. Potosi volcanic series of San Juan Mountains, Colorado								
Z_8 Zircon, Piedra	730		24	8,9,6	7⅔	26		Good
S_7 Sphene	100		40	21	37½	?		Very poor
S_{11} Sphene SC_4	162		21	12	15	240		Very poor
S_{12} Sphene SC_4	152		7½		7½	120		Very poor
P_8 Apatite SC_4	56	2	1	8 (6) 8 3	7	240		Very poor
P_9 Apatite SC_4	54	0.2	0.3	21½ 21	?			Very poor

* Where the age determination is marked "good", the difference between the known geologic age and the calculated age is less than 10 per cent, or 10 million years. In a fair determination, the difference between the ages is from 10 to 50 per cent, and in a poor determination the difference is more than 50 per cent.

It was expected that the two samples would be nearly alike, yet one showed nearly twice the radioactivity and lead content of the other. They give about the same calculated age, average 325 million years ±5 per cent, which makes them Silurian in age.

4. White Mountain magma series, New Hampshire, Carboniferous. Z_{11} from the granite of the quarry at Conway, New Hampshire, contains no detectable sulfides or other impurities. The age determined is 268 million years and is Carboniferous.

5. Contact-metamorphosed marble from the town of Jamaica, Vermont. The marble was completely recrystallized during the metamorphism, which took place in Middle Devonian (?) time. The determined age shoud be the age of the metamorphism. Sample collected and prepared by Dr. John Rosenfeld.

6. Batholith of southern California, middle Cretaceous. Minerals from three different rocks were prepared. The rocks have been described by Larsen (1948) and most of them are represented by analyses. They range in composition from granite to gabbro.

Z_7 El 134 is Lakeview Mountain tonalite.

S_1 Valverde is Bonsall tonalite.

P_2 SLR 299 is hornblende gabbro.

Z_7 from El 134 was the only clean zircon concentrate tested, and it gave a satisfactory age determination.

7. Granite from Snoqualmie Mountains, Washington. The age of the batholith is Miocene. The zircon gave an age of 63 million years, which is much too high. The sample contained enough pyrite to account for the age difference if the pyrite is as rich in lead as some tested.

8. Potosi volcanic series of the San Juan Mountains, Colorado, late Miocene. Z_8, S_{11}, P_8, and P_9 are from the Piedra rhyolite of the San Cristobal quadrangle (SC). S_7 is from the Alboroto rhyolite of the Cochetopa quadrangle (C 2017).

The one zircon, Z_8 gave an age of 26 million years, which is a little too old. Primary lead may account for the indicated great age.

CONCLUSIONS

Table 3 shows that ages of rocks determined by the study of Precambrian or Paleozoic zircons are in good agreement with those estimated from the geology, whereas ages determined by the study of minerals from younger rocks are much greater than those estimated from the geology. This may be partly because a given amount of primary lead in a young zircon

indicates the same number of million years as a similar amount in an old zircon. An error of 30 million years in a Precambrian zircon is only about 5 per cent of the age; in a late Miocene zircon, such an error is 200 per cent

However, it is believed that many of the high age determinations are due to impurities in the samples. The samples tested were more than 99 per cent pure, and the chief impurities were pyrite and molybdenite, and possibly other sulfides. Tests now in progress on impurities obtained by hand-picking or by heating to 450° C and removing impurities with an electromagnet indicate an unexpectedly high lead content in these impurities. Impurities, chiefly pyrite, from eight samples contained approximately 1000 ppm of lead, one was estimated as 100 ppm, and one with much coarse pyrite only 30. Samples with molybdenite contained from 100 ppm or less to 1000 ppm lead. Dust collected in the laboratory contained more than 1000 ppm lead.

A zircon sample with 1 per cent pyrite that contained 100 ppm of lead would have 1 ppm of lead from pyrite. If the pyrite contained 1000 ppm of lead, the sample would have 10 ppm of lead from the pyrite.

All the Precambrian zircons and the zircons from Statesville, North Carolina, were in large crystals, and the samples were free of impurities. They gave good age determinations. The sample from New Hampshire that was available for examination contained no sulfides and only traces of impurities. Some of sample Z_7 from California was available for examination; it contained no sulfides and yielded a satisfactory age determination.

We are now perfecting methods for removing the sulfides and other impurities from some very young zircons of known age and hope to be able to estimate the accuracy of the age determinations. We believe that we can determine the age of zircon with an error much less than 50 million years or 10 per cent of the age.

Most of the apatites tested gave ages that are much too high. This is not surprising, because apatite is low in activity and is more likely than zircon to carry primary lead. Twenty-million-year-old apatite with an average activity would carry less than 0.5 ppm of radiogenic lead. If it were 1000 million years old, it would carry about 15 ppm of lead. Apatite might be expected to carry primary lead, as Pieruccini (1947) has prepared apatite with 0.1 to 0.01 per cent PbO by fusing a mixture of $Ca_3(PO_4)_2$ + $CaCl_2$ and $Pb_3(PO_4)_2$ at 1200° C.

Most of the sphenes gave very high age determinations. The sphene from Renfrew was low, but the data are poor. Sphene appears to be unsatisfactory for age determinations by the method proposed in this paper.

Time and Equipment Required

Only a rough estimate of the time required for an age determination by the method here proposed can be made. With some help in grinding samples and other routine work, an age determination on a rock could probably be made in the equivalent of one man-week. This might be reduced by half by a well-equipped laboratory. The necessary equipment would be a small grinding outfit, an electromagnet, preferably a Frantz Isodynamic separator, equipment for heavy-liquid separations, instruments for alpha counting, a spectrograph suitable for quantitative work, and probably a small flotation cell.

References Cited

Holmes, A. (1947) *The construction of a geological time scale*, Geol. Soc. Glasgow, Tr., vol. 21, pt. 1, p. 117–152.

Larsen, E. S., Jr. (1948) *Batholith and associated rocks of Corona, Elsinore, and San Luis Rey quadrangles, southern California*, Geol. Soc. Am., Mem. 29, 182 pages.

—— and Keevil, N. B. (1942) *Radioactivity and petrology of some California intrusions*, Am. Jour. Sci., vol. 240, no. 3, p. 204–215.

—— — —— (1947) *Radioactivity of the rocks of the batholith of southern California*, Geol. Soc. Am. Bull., vol. 58, p. 483–493.

Pieruccini, Renzo (1947) *Sulla possibilita di introdurre alluminio, ferro, piombo, o molibdeno nel reticolo delle apatiti*, Soc. toscana sci, nat. Atti, vol. 54, p. 256–267.

Simpson, G. G., (1949) *The meaning of evolution*, Yale Univ. Press, 364 pages.

U. S. Geological Survey, Washington 25, D. C.
University of Toronto, Toronto, Ontario
University of Rhode Island, Kingston, R. I.

Manuscript Received by the Secretary of the Society, January 21, 1952.
Project Grants 296/39, 381/41/S36.
Publication Authorized by the Director, U. S. Geological Survey.

lead,
nary
atite
min-
)n at

age
was
rs to
s by

uired
here
rind-
age
y be
This
pped
ld be
gnet,
ator,
, in-
graph
bly a

ogical
l. 21,

ciated
Ray
Soc.

and
Am.

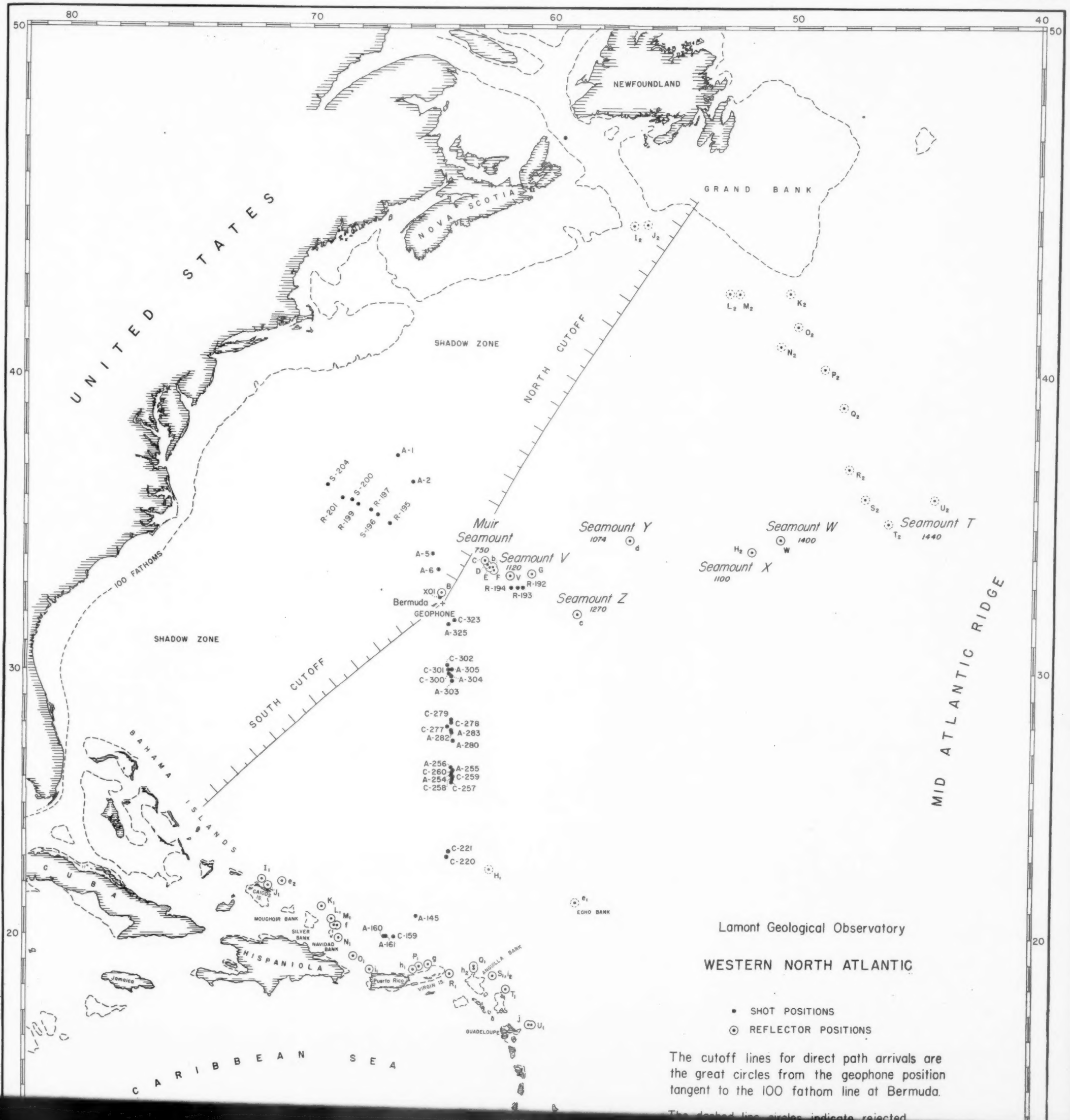
ks of
Soc.

intro-
so ed
nat.

ution.

D. C.:
ARIO;
R. I.
y ren

U. S.



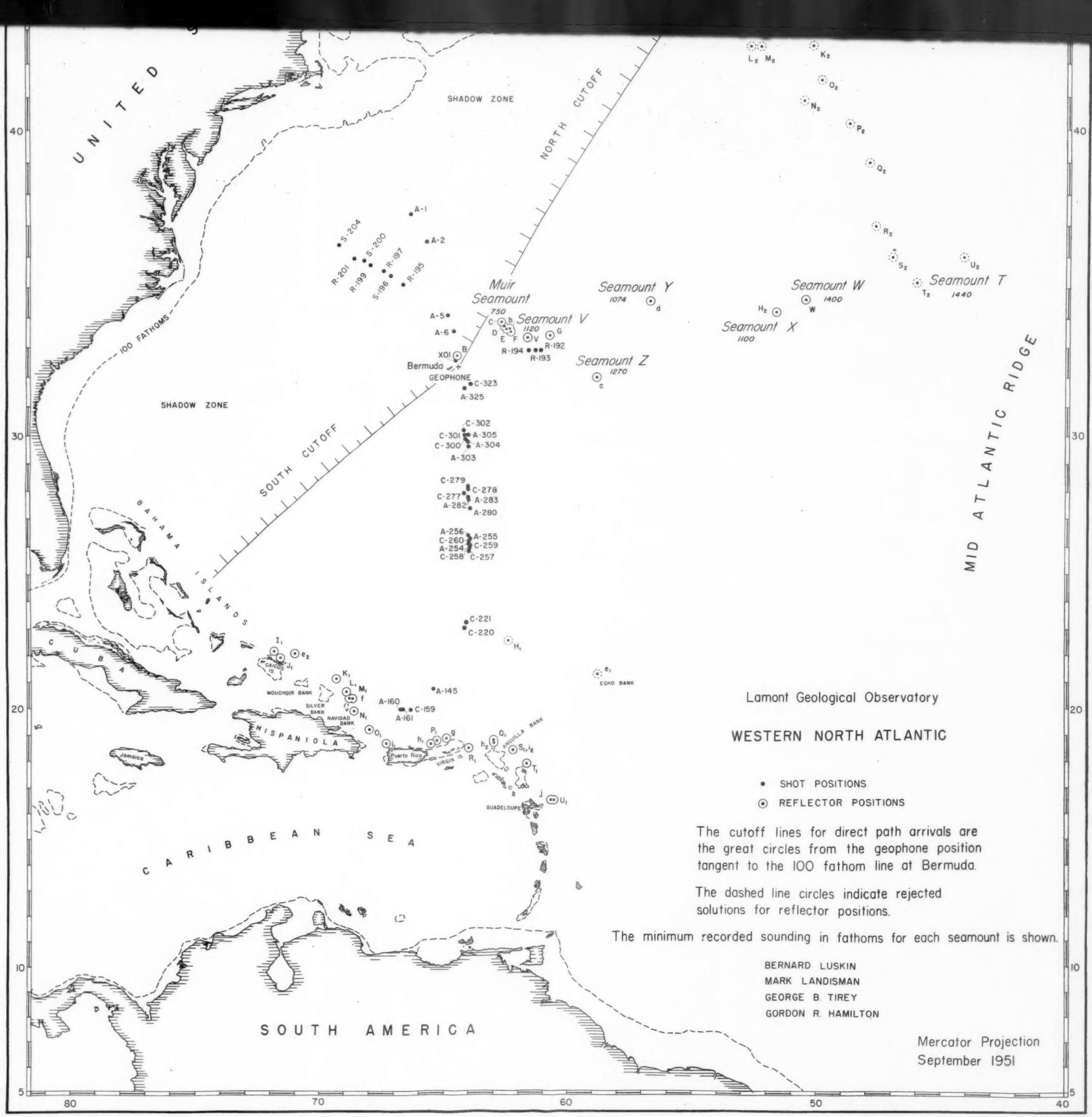
Lamont Geological Observatory

WESTERN NORTH ATLANTIC

- • SHOT POSITIONS
- ⊙ REFLECTOR POSITIONS

The cutoff lines for direct path arrivals are the great circles from the geophone position tangent to the 100 fathom line at Bermuda.

The dashed line circles indicate rejected



Lamont Geological Observatory

WESTERN NORTH ATLANTIC

- • SHOT POSITIONS
- ⊙ REFLECTOR POSITIONS

The cutoff lines for direct path arrivals are the great circles from the geophone position tangent to the 100 fathom line at Bermuda.

The dashed line circles indicate rejected solutions for reflector positions.

The minimum recorded sounding in fathoms for each seamount is shown.

BERNARD LUSKIN
MARK LANDISMAN
GEORGE B. TIREY
GORDON R. HAMILTON

Mercator Projection
September 1951

CHART OF WESTERN NORTH ATLANTIC OCEAN SHOWING SHOT AND REFLECTOR POSITIONS

SU

Subm
over 200
second b
case but
the struc
eral sean
in the vi
another
Discover

Introduc
Acknowl
Theory. .
Correlati
Reflector
Conclusio
Referenc

Figure
1. Relati
corder
2. Ray
Sound
3. Echoe

Plate
1. Chart
showir
2. Shot r
a recei
3. Echoes

This
sounds w
plosive s
over a p
submarin
echoes, h
shots wi
They arr
tively id
great cir

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 63, PP. 1053-1068, 3 FIGS., 8 PLS. OCTOBER 1952

SUBMARINE TOPOGRAPHIC ECHOES FROM EXPLOSIVE SOUND

BY BERNARD LUSKIN, MARK LANDISMAN, G. B. TIREY, G. R. HAMILTON

ABSTRACT

Submarine echoes of explosive sound are received which show abundant signal strength after traveling over 2000 miles total path from a 50-pound shot source; predominant frequencies are in a 5 to 50 cycle per second band. With certain basic assumptions, the reflector positions for the echoes are calculated. In every case but one, these positions correspond to known submarine structures with steep gradients. Most of the structures are the steep submarine slopes of the islands surrounding the northeastern Caribbean. Several seamounts to the east of Bermuda are reflectors. It is concluded that there is an uncharted seamount in the vicinity of 33° 22′ North Latitude, 60° 48′ West Longitude. Significant echoes are received from another seamount on which the least recorded sounding (probably not the actual peak) is 1270 fathoms Discovery of shoal areas and submarine structures can be greatly facilitated by the use of submarine echoes.

CONTENTS

TEXT

	Page
Introduction	1053
Acknowledgments	1056
Theory	1056
Correlation of echoes	1057
Reflector positions	1062
Conclusions	1067
References cited	1068

ILLUSTRATIONS

Figure	Page
1. Relative frequency response of Tusk recorder	1055
2. Ray diagram of typical Atlantic Ocean Sound Channel	1058
3. Echoes of Caryn-Atlantis Shots	1059

Plate	Facing page
1. Chart of Western North Atlantic Ocean showing shot and reflector positions	1053
2. Shot record showing reception of sound by a receiver on a submarine slope	1056
3. Echoes of Rehoboth-San Pablo shots	1060
4. Echoes of Rehoboth-San Pablo shots	1061
5. Echoes of Rehoboth-San Pablo shots	1066
6. Echoes of Rehoboth-San Pablo shots	1067
7. Echoes of Rehoboth-San Pablo shots	1068
8. Echoes of Rehoboth-San Pablo shots	1069

TABLES

Table	Page
1. Hydrographic Data	1054
2. Travel Time Data—Caryn-Atlantis Shots	1060
3. Travel Time Data—Rehoboth-San Pablo Shots	1061
4–14. Reflectors—Caryn-Atlantis Shots (Facing page)	1062
15–35. Reflectors — Rehoboth-San Pablo Shots (Facing page)	1064
36. Rehoboth-San Pablo Shots East of Bermuda	1065
37. Atlantis Shots North of Bermuda	1066
38. List of Known Reflectors and Symmetrical Solutions	1067

INTRODUCTION

This work is concerned with the study of sounds which emanate from a submerged explosive source and propagate through the ocean over a path which includes a reflection from a submarine structure. These reflected sounds, or echoes, have been observed on records made of shots with deep-water recording equipment. They arrive after the signal, which can be positively identified as having traveled over the great circle path from source to receiver, and may have travel times up to about 50 minutes. According to Ewing and Worzel (personal communication), similar echoes from Cat Island with a delay of about 100 seconds were observed at the Eleuthera Island Sofar Station in 1945. Ewing, Press, and Worzel (1951) have shown that earthquake-generated *T* phases occasionally produce reflections from submarine structures.

During the period May 9–22, 1951, the research vessels CARYN and ATLANTIS made several refraction stations in the area between

TABLE 1—HYDROGRAPHIC DATA

Shot No.	Charge Size, Lbs.	Shot Depth, Fathoms	Latitude North		Longitude West		Shot Time (Greenwich)			
			Degs.	Mins.	Degs.	Mins.	Date 1951	Hr.	Min.	Sec.
Caryn-Atlantis										
A-145	100	70	20	41.6	65	25.0	May 9	22	36	04
C-159	100		19	55.7	66	22.3	May 11	16	02	16
A-160	100		19	56.5	66	45.6	May 11	17	18	02
A-161	100		19	57.5	66	41.0	May 11	18	01	52
C-220	50	0	23	01.8	64	10.1	May 18	05	47	52
C-221	50	130	23	13.9	64	07.4	May 18	07	15	49
A-254	50	315	26	07.3	64	02.2	May 19	17	06	27
A-255	50	305	26	14.5	64	02.7	May 19	18	12	07
A-256	300	50	26	25.7	64	02.7	May 19	20	47	00
C-257	50	0	25	52.	63	59.	May 19	22	35	43
C-258	50		25	58.	63	59.	May 19	23	21	07
C-259	50		26	05.	63	59.	May 20	00	27	03
C-260	50	235	26	14.	63	59.	May 20	01	20	46
C-277	50	200	27	55.	64	04.	May 20	16	28	23
C-278	50	205	28	05.	64	04.	May 20	17	36	01
C-279	50	275	28	11.	64	05.	May 20	18	16	45
A-280	250	235	27	25.	63	57.	May 20	19	37	39
A-282	50	300	27	40.	63	59.	May 20	22	14	52
A-283	50	275	27	47.5	64	01.	May 20	23	22	41
C-300	50	245	29	52.8	64	12.	May 21	15	41	21
C-301	50	215	30	01.0	64	13.	May 21	16	45	04
C-302	250		30	11.5	64	15.2	May 21	18	07	23
A-303	250		29	36.	64	03.5	May 21	20	14	52
A-304	250	250	29	45.1	64	04.5	May 21	21	32	42
A-305	50	295	30	00.	64	06.5	May 21	23	16	48
C-323	50	195	31	45.	63	57.	May 22	16	30	17
A-325	50	335	31	37.2	64	12.5	May 22	21	18	08
X01	50	600	32	33.5	64	35.6	July 6	16	55	38
Rehoboth-San Pablo										
R-195	550	761	35	06.2	66	39.0	April 28	22	13	13
S-196	600	738	35	23.3	67	11.6	April 29	00	14	08
R-197	700	713	35	30.6	67	28.0	April 29	01	13	44
R-199	700	722	35	43.0	67	59.9	April 29	03	13	38
S-200	600	713	35	52.0	68	14.8	April 29	04	13	26
R-201	700		35	56.2	68	38.8	April 29	05	13	28
S-204	770	797	36	22.0	69	19.0	April 29	08	13	33
Rehoboth										
R-192	550	717	32	54	61	11	April 27	20	12	43
R-193	550*	576	32	54	61	25.3	April 27	21	13	04
R-194	550	752	32	54	61	40	April 27	22	12	16
Atlantis										
A-1	300	620	37	21.3	66	22.5	August 14	06	45	07
A-2	300	682	36	28.5	65	44.0	August 14	11	39	21
A-5	300	616	34	05.0	64	54.0	August 15	03	08	40
A-6	300	740	33	31.8	64	38.0	August 15	07	06	12

* Partial detonation

Puerto Rico and Bermuda. In the course of this work, many charges containing 50 or more pounds of explosives were fired, and from each

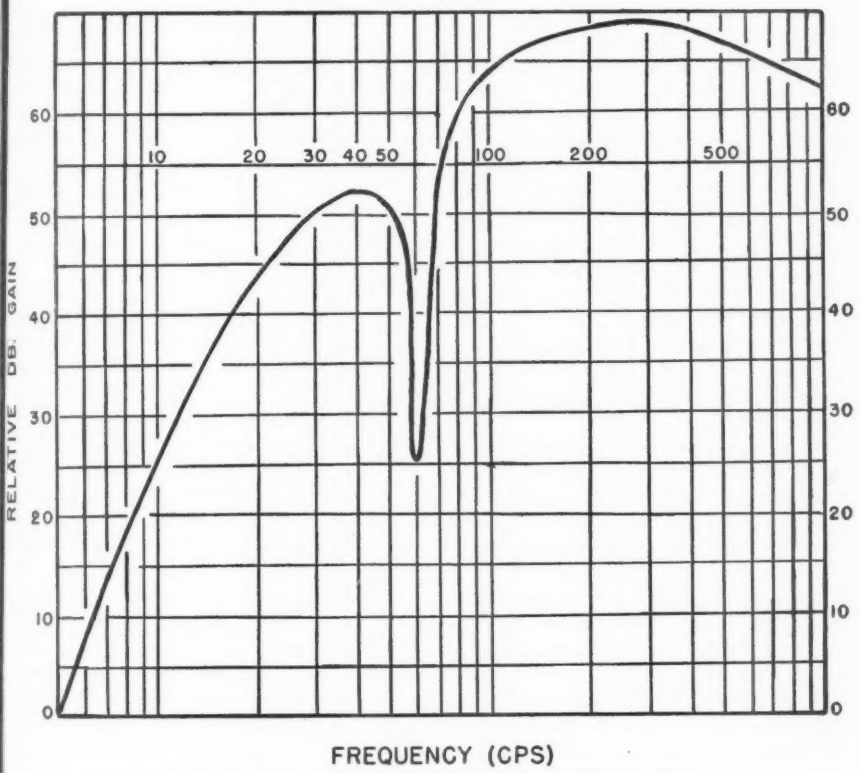


FIGURE 1.—RELATIVE FREQUENCY RESPONSE OF TUSK RECORDER

several strong echo signals were recorded at the Columbia University Geophysical Field Station in Bermuda. The records of 27 of these shots are included in this study.

On April 28–29, 1951, the U. S. Navy Hydrographic Office ships, USS REHOBOTH and USS SAN PABLO fired a series of larger charges along a line to the northwest of Bermuda. As many as 20 different strong echo signals were received from these shots. The records of seven shots are included in the data.

In addition, one 50-pound shot fired offshore at Bermuda by G. B. Tirey, four 300-pound shots fired by J. L. Worzel from the ATLANTIS on August 14–15, 1951, to the north of Bermuda, and three 550-pound shots fired by the USS REHOBOTH to the east of Bermuda are studied here.

The positions of all these shots are shown in Plate 1. The north and south cut-off lines for sound-channel arrivals to the Bermuda receiver are also shown. These correspond to the great-circle paths from the receiver tangent to the 100-fathom curve. The shot data are tabulated in Table 1. The positions given in the tables are believed to be accurate to within 2 miles. The shot times are known accurately to a few hundredths of a second but are given here to the nearest second.

The records selected are for those shots for which the quality of the data is high. Some of the rejected shots were duds or partial detonations. In other cases the shot times were only

approximately known, the recorder noise level was very high, or the recording equipment broke down.

The recording equipment which monitored these shots includes a geophone in 435 fathoms of water, connected by more than 6 miles of cable to a shore installation where the geophone signal is amplified and channelled to various recorders. Among the latter is a specially designed optical recorder, designated TUSK, which gives an 8-inch by 43-foot record of a galvanometer trace every 24 hours, at a paper speed of 16 inches per minute. The absolute calibration of this recording system is not available, but the relative frequency response is shown in Figure 1. Records were also obtained on a Brush recorder. The relative frequency response for the latter is essentially the same as shown in Figure 1 up to 100 cycles per second, after which the response falls off sharply.

The echo signals received from the shots listed have been correlated by matching corresponding total and relative travel times and signal character. The positions of the reflectors have been calculated with certain basic assumptions. It was found that the reflectors, in all cases but one, correspond to areas of known steep submarine slopes. One reflector does not correspond to any charted submarine structure. Most of the reflectors for the echoes studied here are along the northern coast of the Bahama Islands and the islands surrounding the northeastern Caribbean Basin. At least two seamounts on which no soundings less than 750 fathoms have been made are evidently good reflectors, and one seamount whose least recorded sounding is 1270 fathoms gives a definite echo. It is suggested that the latter seamount probably rises much higher than the minimum sounding recorded.

Acknowledgments

Professor Maurice Ewing, Director of the Lamont Geological Observatory of Columbia University, is the sponsor of this project and contributed invaluable advice and criticism.

Dr. J. Lamar Worzel, of the Lamont Geological Observatory of Columbia University, was of great aid in the preparation of the manuscript.

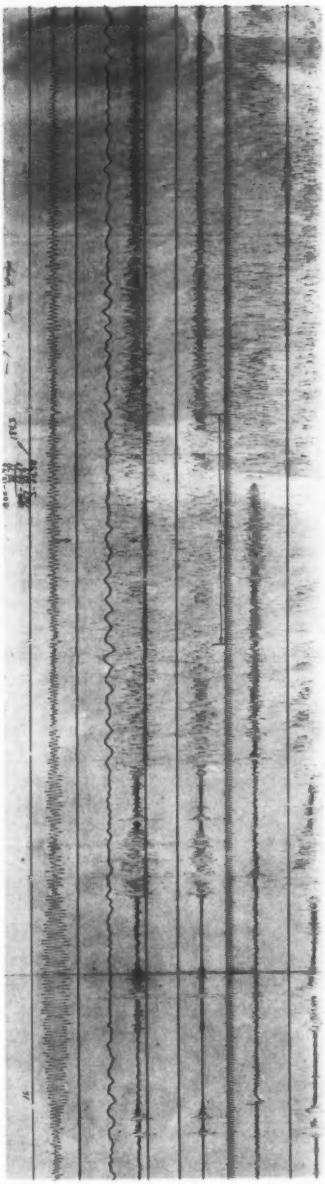
The splendid cooperation of the officers and men of the Research Vessels Caryn and Atlantis, and the U. S. Navy Hydrographic office ships, USS. Rehoboth and USS. San Pablo, made this work possible. In particular, the authors are indebted to Paul C. Wuenschel, of the Lamont Observatory, for supplying the navigational data of the Caryn-Atlantis cruise, and to David F. Barnes, Geophysicist of the U. S. Geological Survey, for the navigational and shot data of the Rehoboth-San Pablo cruise.

This work was supported jointly by the Office of Naval Research and the Bureau of Ships.

Theory

In 1944, Ewing and Worzel (1948) demonstrated that explosive sound in the ocean may be heard over very great distances through utilization of the natural sound channel. At about 700 fathoms depth in the Atlantic Ocean, a minimum exists in the sound velocity, resulting from the temperature distribution above 700 fathoms depth and from the effects of pressure below this depth. Explosive sound, originating at this depth of minimum velocity (the axis of the sound channel), may be refracted back and forth across the axis without contacting either the surface or bottom of the ocean and thus propagate with very small attenuation. This type of sound propagation is referred to as "sound-channel transmission". In the original work, a one-half-pound bomb, fired at the depth of the axis, was heard with abundant signal strength at more than 800 miles, a 4-pound bomb at 2300 miles, and a 6-pound charge at 3100 miles by a receiver in the sound channel. Furthermore, extrapolation of the data indicated a range of at least 10,000 miles for a 4-pound charge.

The character of a direct sound-channel signal, as seen on an oscillograph record, is quite distinctive. The sound rays which originate from the source making the greater angles with the axis travel with higher velocities over the longest actual paths, cross the axis few times, and arrive first. The rays making shallow angles with the axis travel with the lower velocities, over shorter actual paths, cross the axis many times, and arrive later. The time separation between arrivals becomes less and less as the number of axial crossings increases, causing a



SHOT RECORD SHOWING RECEPTION OF SOUND BY A RECEIVER ON A SUBMARINE SLOPE

final accumulation of arrivals which cease abruptly. Accordingly, the oscillograph records show first arrivals of low intensity with long intervals between them and higher intensities as the intervals shorten until the peak intensity is reached. After these the signal level drops sharply.

Other work done by this group, as yet unpublished, has indicated that the bottom of the deep ocean is a very good reflector for low-frequency sound, and that the surface is an almost perfect reflector. Thus, it is also possible to obtain great ranges (though not comparable with those for sound-channel propagation) for sounds which travel by reflecting successively from top and bottom of the ocean.

Figure 2 (Ewing and Worzel, 1948) shows the ray diagram typical Atlantic Ocean sound channel. For a surface shot, the sound rays must cross the axis with angles of 12.2° or greater. Those rays which make angles with the axis between 12.2° and 15.19° are refracted below the axis and surface reflected; those making angles greater than 15.19° are successively reflected from the bottom and the surface. Essentially, no rays from a surface shot may travel by sound-channel transmission, although, after reflection from a submarine structure, a great part of the reflected sound energy received at a distant point is probably confined to the sound channel. Shot C-257, for example, a 50-pound surface shot, produced an echo which was received with abundant signal strength after a travel time of 1615 seconds. The total path for this signal is at least 1250 miles. Furthermore, strong direct path signals have been received regularly at the Geophysical Field Station (Bermuda) from one-half-pound surface shots as far away as 300 miles.

Sound rays impinging on a sloping bottom that rises to the ocean surface can be reflected from the bottom and the surface until an angle of incidence is obtained with either the bottom or the surface which reverses their direction of travel. Obviously, the steeper the slope, the fewer top and bottom reflections before the required incidence is obtained to make the rays reverse direction in a horizontal sense. Hence, a gently inclined slope must extend much nearer the surface than a steep one in order to produce an echo.

Plate 2 shows a signal received by a geophone lying on a 6-degree slope. The record is that made from a 1-pound shot fired at a depth of 600 fathoms, 143 miles from the geophone which lies in 435 fathoms of water. The distinct forerunning bursts of a typical sound-channel signal are clear. The characteristic sound-channel cut-off is followed, however, by sound which has traveled up the slope, has been reflected, and has returned to the geophone as an echo.

It is well to consider here several highly variable factors upon which the reception of an echo signal is dependent. Among these are: size, depth, and efficiency of detonation of the explosive charge; length of the path; presence or absence of submarine structures along the path which may "shadow" the reflector from the shot or receiver; the structure of the reflector; its slope, lithology, and physical configuration; finally, the efficiency of the recording system, that is, the signal to noise ratio. The physical configuration of the reflector, in particular, determines whether there is a sufficiently large area with a favorable horizontal angle of incidence for a particular receiver and shot point. In consideration of these factors, it is to be expected that the pattern of echoes received will depend greatly on the relative and absolute positions of the shot and receiver in the ocean.

Several reasons suggest themselves for the predominantly low-frequency character of echo signals: (1) The absorption coefficient for low-frequency sound in the ocean is smaller than for the higher frequencies; (2) High-frequency sound is scattered to a greater degree in propagating through the water; (3) The effective bottom-reflection coefficient for low-frequency sound is much higher than for higher frequencies for incidence beyond the critical angle on a slightly rough bottom. Thus the low-frequency sound may propagate with small attenuation by top and bottom reflection as well as by sound-channel transmission. (4) The discontinuities and irregularities of an actual subsurface slope tend to scatter the shorter wave-length sound and leave the longer wave lengths relatively unaffected.

Correlation of Echoes

The shots fired by the Caryn and Atlantis between Puerto Rico and Bermuda are in groups spaced at fairly regular intervals and

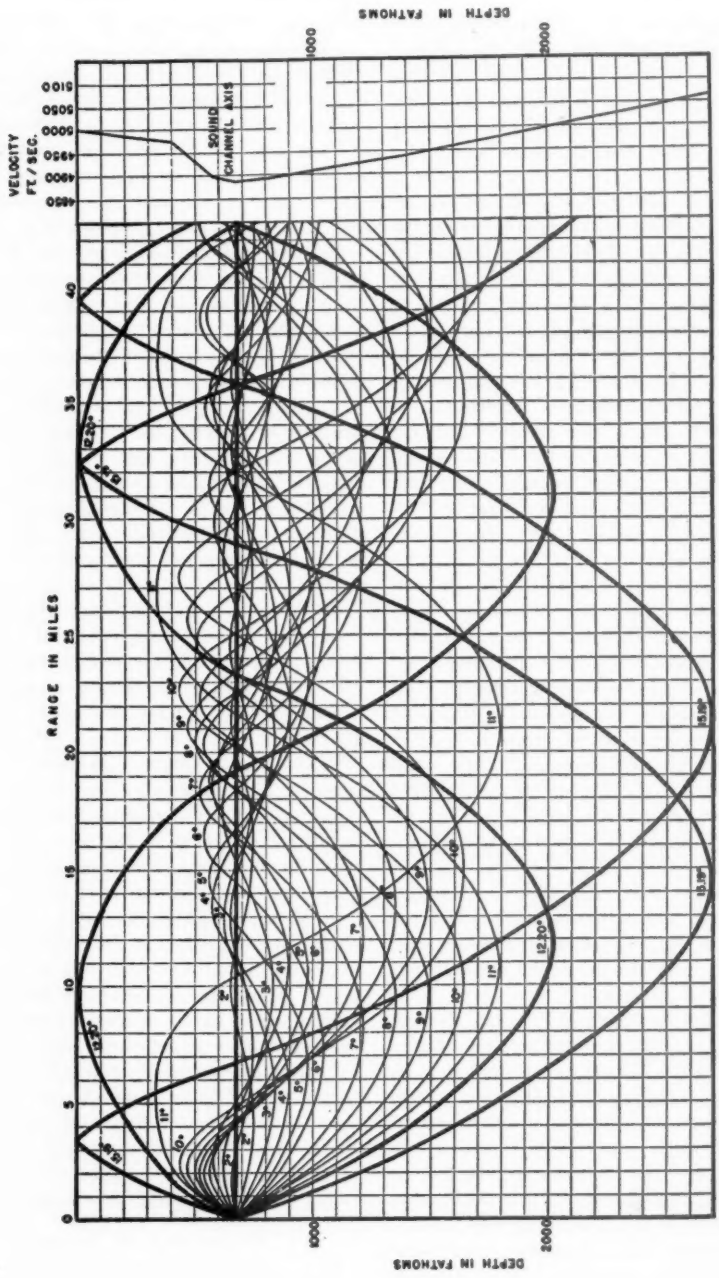


FIGURE 2.—RAY DIAGRAM OF TYPICAL ATLANTIC OCEAN SOUND CHANNEL—SOUND CHANNEL AND REFRACTED SURFACE-REFLECTED RAYS

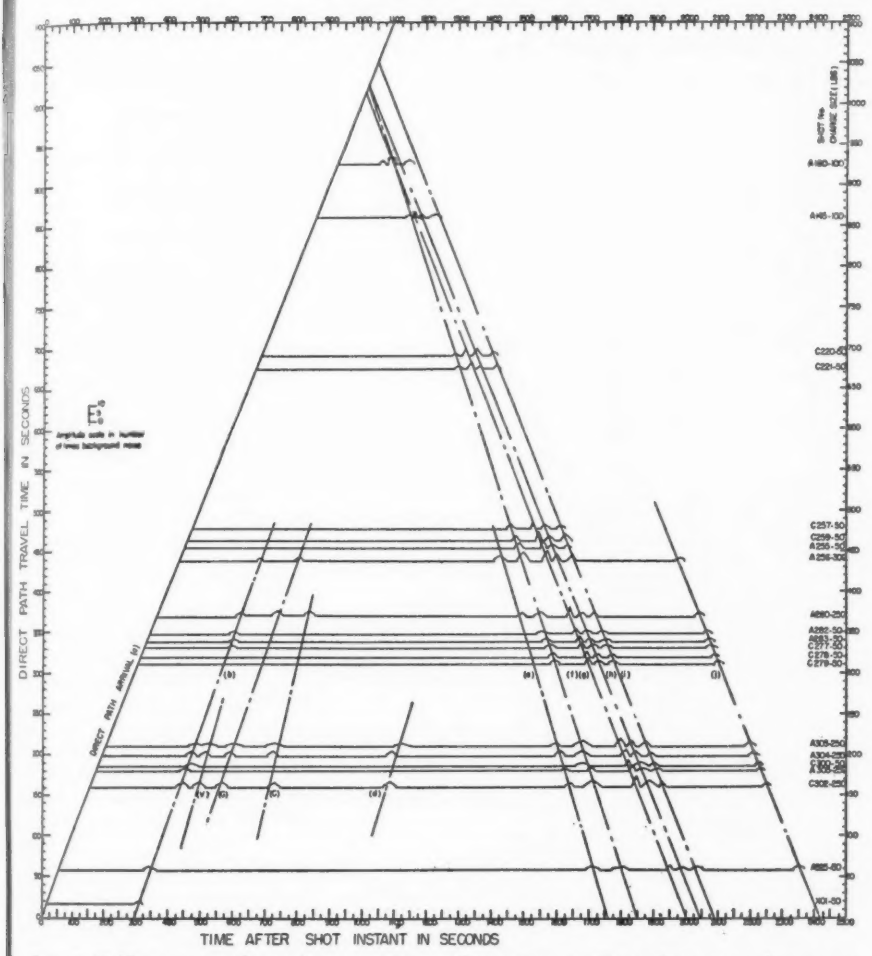


FIGURE 3. ECHOES OF CARYN-ATLANTIS SHOTS—CHARACTER OF ECHO SIGNALS IS SHOWN BY AMPLITUDE AND SIGNAL DURATION ABOVE BACKGROUND NOISE

approximately in a straight line which passes through the receiver position. The most distinctive feature of the records from these shots is a group of four echoes (Fig. 3) designated *f*, *g*, *h*, and *i*, which arrived from 20 to 30 minutes after shot time. The first, third, and fourth echoes in this group are long, drawn-out signals and rise to a maximum amplitude of two to four times background level. The second echo, *g*, however, is relatively sharp. It rises to maximum amplitudes of four to seven times background and generally lasts about 15 seconds, where *f*, *h*, and *i* are 25 seconds in duration. This group of echoes can be correlated for the shot records over the entire track.

Beginning with shot No. A256, seven new echo signals appear, three of which, *b*, *e*, and *j*, are on the records of as many as seven shots. All these signals are of drawn-out character lasting from 15 to 30 seconds and rising to maximum amplitudes of two to three times background. Echoes *c*, *d*, *V*, and *G* appear on records of only three to five of the biggest shots which are close to the Bermuda end of the

track. These four echoes, together with echo *b*, form an early-arrival group for which travel time decreases with decreasing distance of the shot from Bermuda. Echoes *e* and *j*, together with *f*, *g*, *h*, and *i*, form a late-arrival group for which travel time increases as the shot positions approach Bermuda.

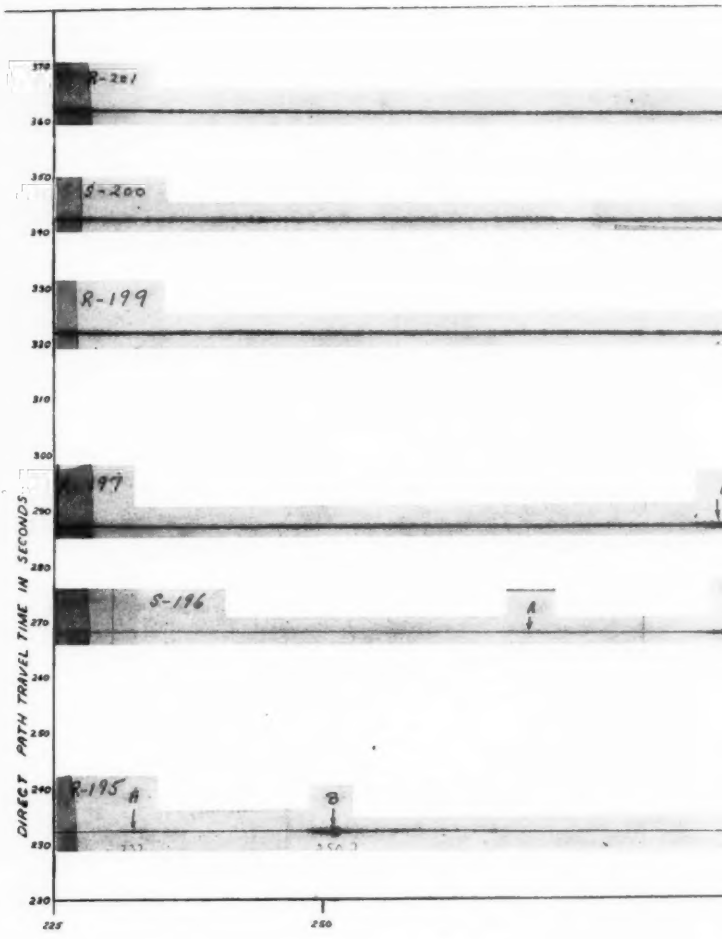
To discuss travel times of echo signals, it is necessary to establish some criterion for picking the time of arrival. The emergence from and submergence into the background noise level is too gradual in most cases to provide a basis for picking consistent arrival times. The most distinctive characteristic of the echo signal is the part which has the maximum amplitude and usually occurs somewhere near the midpoint. In most cases, this point, referred to hereafter as the maximum, is indefinite to the extent that the arrival time may be varied as much as 10 seconds. However, the pick of the maximum gives enough consistency to the data to provide a workable criterion for discussion and utilization of echo travel times.

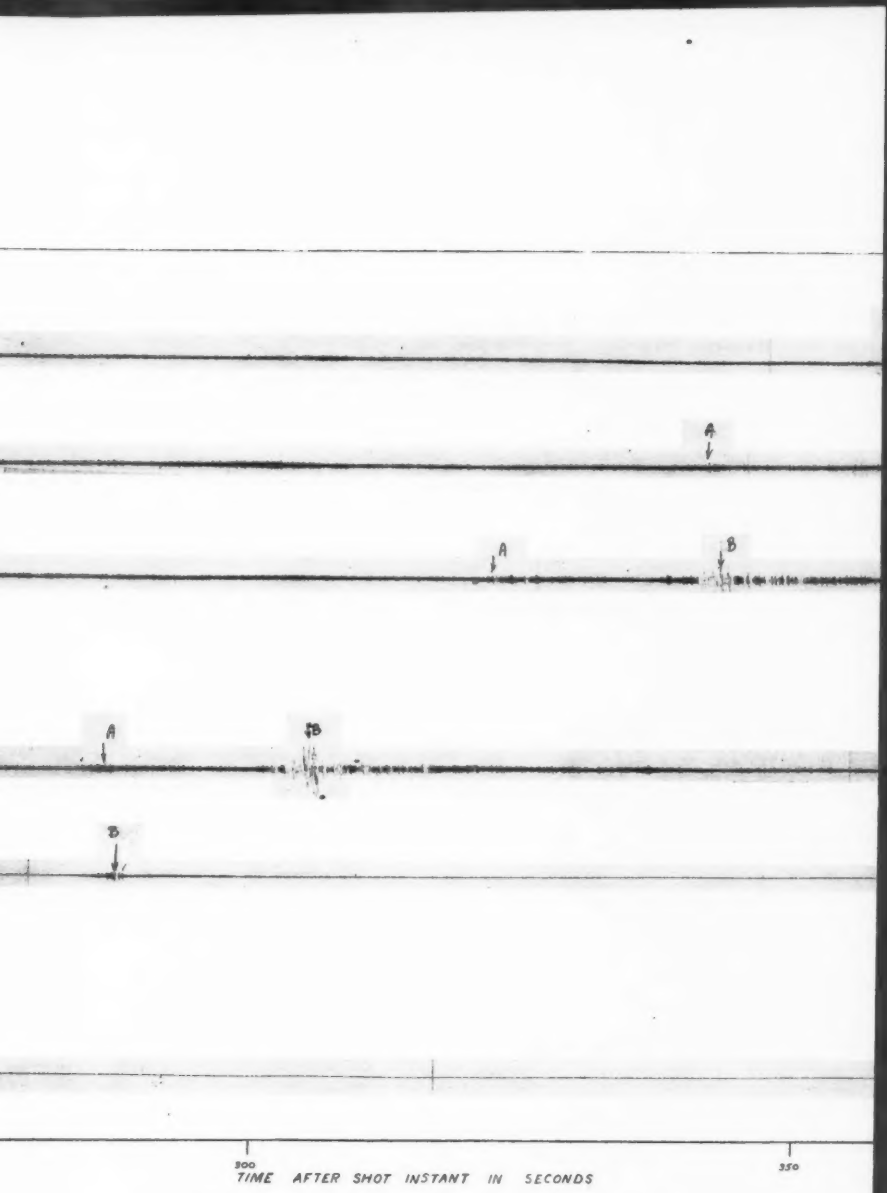
The travel times of the echoes from the CARYN-ATLANTIS shots are shown in Table 2. These are all taken from TUSK records which, unfortunately, are not suitable for reproduction. Figure 3 is a composite plot of the echo arrivals, showing arrival times and signal character. The signal character is shown schematically; the maximum amplitude and signal duration are the same as measured. In most

TABLE 2—TRAVEL TIME DATA—CARYN-ATLANTIS SHOTS

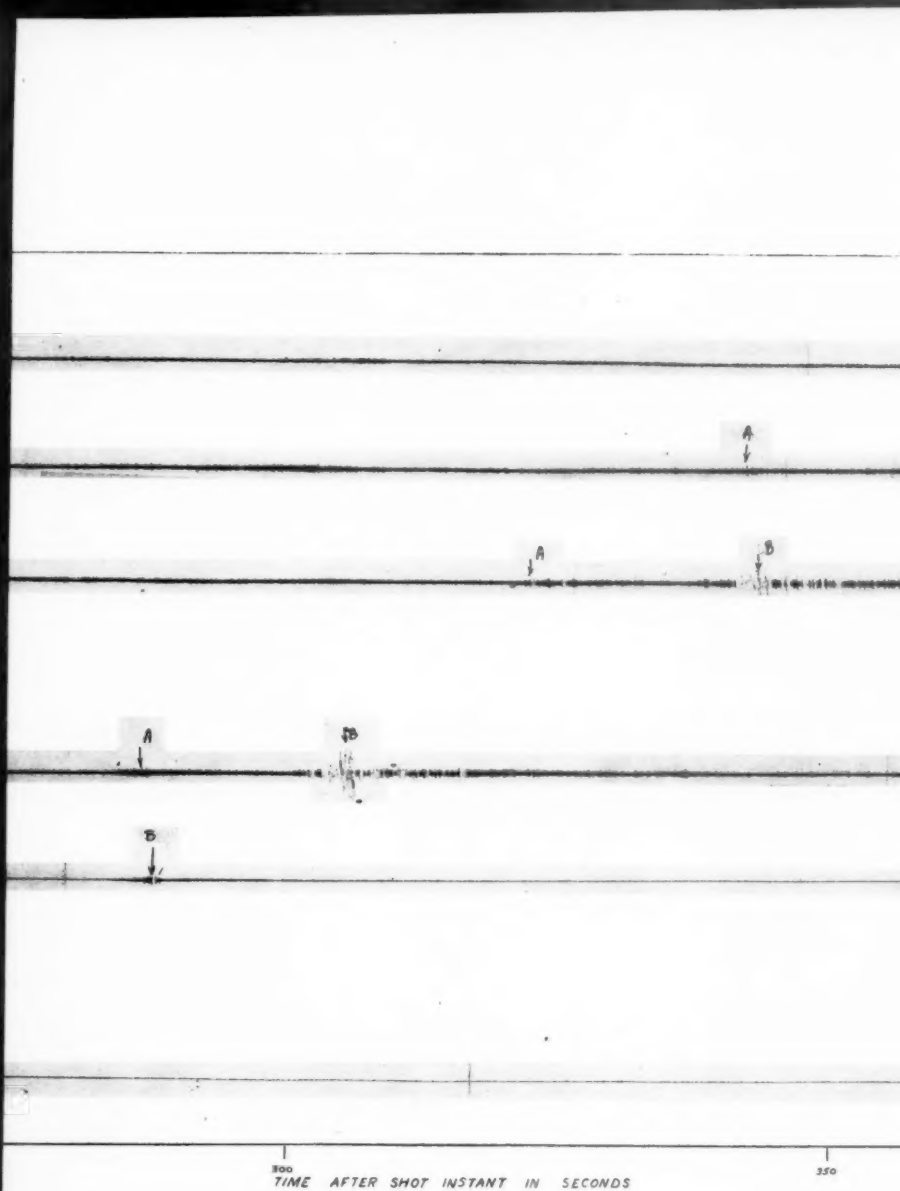
Shot No.	Charge Size Lbs.	Shot Depth, Fathoms	Travel Time in Seconds											
			a	b	V	G	c	d	e	f	g	h	i	j
A-145	100	70	860							1150	1154	1185*	1126*	
C-159	100		923							1081	1140	1145	1145	
A-160	100		926							1065	1146	1146	1146	
A-161	100		925							1072	1145	1145	1145	
C-220	50	0	691							1289	1319	1352	1419	
C-221	50	130	675							1298	1338	1364	1426	
A-254	50	315	464							1477	1545	1577	1626	
A-255	50	305	454							1478	1556	1587	1633	
A-256	300	50	438	695		809			1451	1490	1572	1602	1646	1983
C-257	50	0	478							1464	1529	1566	1615	
C-258	50		473							1471	1541	1576	1628	
C-259	50		463							1476	1546	1579	1630	
C-260	50	235	453							1480	1553	1587	1632	
C-277	50	200	331	600						1583	1677	1716	1758	2081
C-278	50	205	319							1590	1691	1730	1771	2094
C-279	50	275	311							1595	1699	1731	1778	2104
A-280	250	235	369	639		737	836		1495	1555	1641	1681	1718	2044
A-282	50	300	348	605						1556	1661	1693	1743	2066
A-283	50	275	338	608						1573	1672	1704	1751	2074
C-300	50	245	186	471						1684	1821	1863	1903	2226
C-301	50	215	176	456						1701	1831	1869	1915	2238
C-302	250		160	446	494	570	732	1086	1643	1711	1846	1889	1929	2253
A-303	250		210	484	525	604	735	1100	1604	1682	1800	1834	1879	2200
A-304	250	250	198	474	519	594	729	1092	1611	1681	1815	1845	1894	2212
A-305	250	295	180	455					1628	1710	1833	1869	1912	2232
C-323	50	195	58	336	383					1834	1973	2004	2050	2370
A-325	50	335	58	340					1711	1808	1950	1988	2034	2352
X01	50	600	16	314										

* Two arrivals on shot A-145 with 1258 and 1332 seconds travel time are identified as h_2 and i_2 respectively.

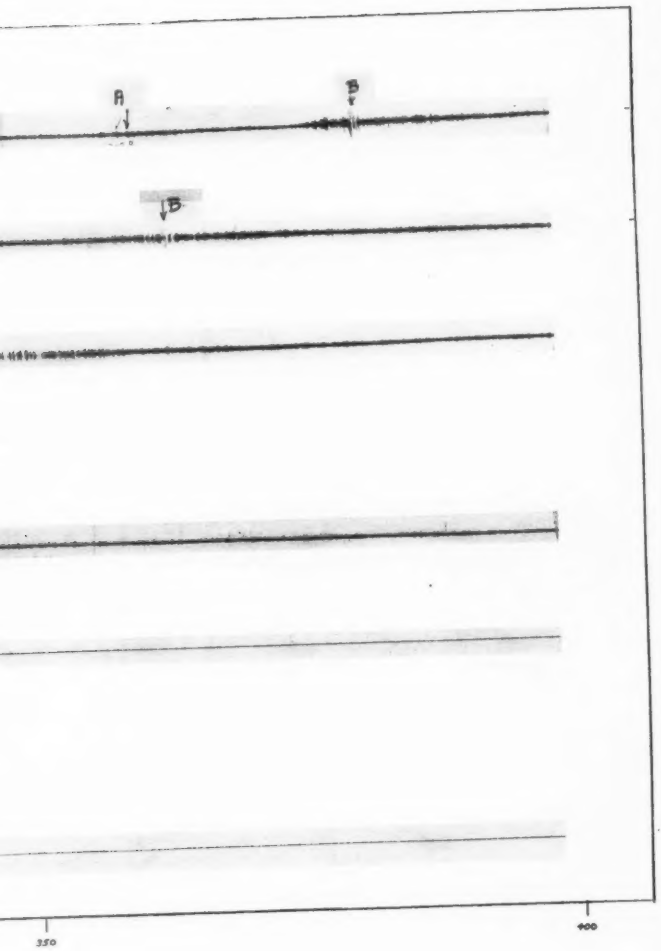

DIRECT PATH TRAVEL TIME IN SECONDS
370
360
350
340
330
320
310
300
290
280
270
260
250
240
230
220
225
250
R-201
S-200
R-199
197
S-196
A
R-195
A
B

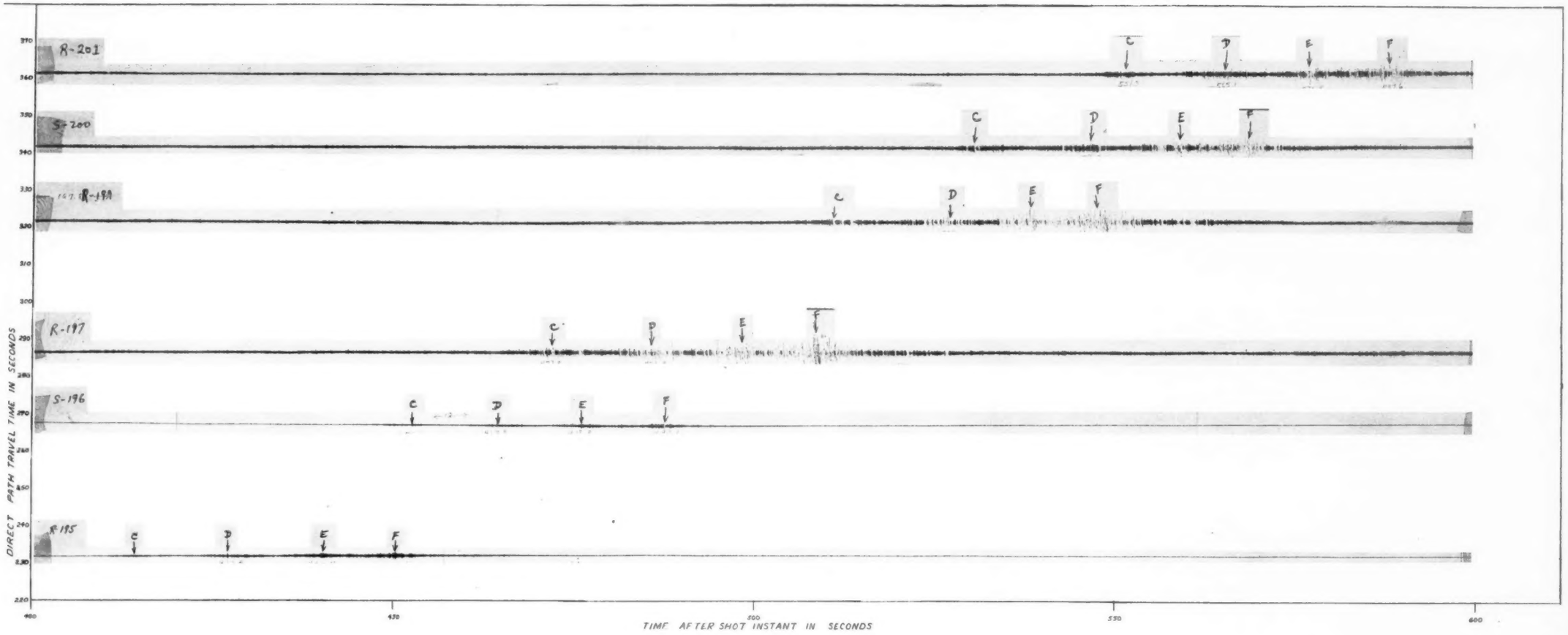


ECHOES OF REHOBOTH - SAN PABLO SHOTS



ECHOES OF REHOBOTH - SAN PABLO SHOTS


A
B
B
350
400



ECHOES OF REHOBOTH - SAN PABLO SHOTS

cases, th
nal lasts
The s
USS SA

Shot No.
Charge Si
Shot Dep

* Cl

are ap
northw
point
Brush
Plates
R-195
For c
parts
time
one-h
ceive
V, do
the d
the sl
rupte
the fi
partly
The f
the d

cases, the maximum amplitude part of the signal lasts 10 to 15 seconds.

The shots fired by the USS REHOBOTH and USS SAN PABLO to the northeast of Bermuda may be divided into four categories: a group of four arrivals, *C*, *D*, *E*, and *F*, which travel 6–10 minutes; a scattered group of three echoes, *V*, *G*, and *H*, of small amplitude and travel

TABLE 3—TRAVEL TIME DATA—REHOBOTH-SAN PABLO SHOTS

Shot No.	R195	S196	R197	R199	S200	R201	S204
Charge Size, Lbs.	550	600	700	700	600	700	770
Shot Depth, Fathoms	761	738	713	722	713		797
A	232	268	287	322	342	362	412
B	250	287	305	343	363	380	432
C	415	455	472	511	531	551	604
D	427	467	486	526	546	565	617
E	441	479	498	539	559	576	630
F	450	490	509	548	568	587	639
G	630	669	687	728	747	768	818
H	*	1737	1754	1789	1804	1823	1863
I	1908	1916	1919	1924	1929	1932	1947
J	1951	1958	1963	1965	1972	1975	1985
K	1968	1980	1984	1994	2000	2006	2032
L	2016	2031	2038	2051	2060	2063	2091
M	2038	2058	2063	2079	2088	2098	2119
N	2085	2113	2120	2137	2147	2156	2183
O	2198	2217	2223	2243	2256	2260	2295
P	2230	2255	2264	2290	2304	2314	2356
Q	2262	2293	2295	2322	2332	2351	2379
R	2280	2308	2320	2346	2362	2367	2398
S	2322	2348	2363	2384	2407	2416	2451
T	2421	2445	2461	2493	2508	*	2562
U	2653	2680	2692	2723	2739	2753	2794
V			593	610–640	630–650		721

* Changing record paper

are approximately in a straight line running northwest-southeast, which passes through a point 80 to 100 miles north of the receiver. The Brush records of six of these shots are shown in Plates 3–8. The gain setting on shot records R-195 and S-196 is one-tenth that of the others. For convenience of illustration, insignificant parts of the records are not shown, and the time scale on Plates 5 and 8 is compressed by one-half. Twenty-one distinct echoes were received from these shots, only one of which, *V*, does not appear on all the shot records. All the direct great-circle deep-water paths from the shot positions to the geophone are interrupted by the Bermuda Islands. Consequently, the first (direct-path) arrival, *A*, has traveled partly through rock and is greatly attenuated. The first echo arrival, *B*, is at 20 seconds after the direct-path arrival. The remaining echoes times up to 30 minutes; a large group of 11 very strong echo signals, *I*, *J*, *K*, *L*, *M*, *N*, *O*, *P*, *Q*, *R*, and *S*, with travel times up to 40 minutes; a group of two echoes, *T* and *U*, which arrive very late, 40–47 minutes after shot time. For all the echoes received, travel time increases with increasing shot distance from the receiver (Table 3).

The two series of echoes described above, referred to as the *C-A* (CARYN-ATLANTIS) and *R-S* (REHOBOTH-SAN PABLO) series, respectively, are used independently to calculate the positions of the reflecting structures. Since there is no means of knowing beforehand that the echo patterns are similar, the *C-A* and *R-S* series are not correlated on the basis of signal character and relative travel time. There is good correspondence between the reflector positions calculated independently from the

two series, but there are also appreciable divergences. Seamounts *Z* and *Y* (Pl. 1), for example, are located from the *C-A* series as reflectors, but no *R-S* echo correlates with them. The opposite case applies to echo *H*, from seamount *X*, which does not correlate with any *C-A* echo.

Echoes from shots *R*-192, *R*-193, and *R*-194 (*R*, REHOBOTH series), fired along a line of latitude to the east of Bermuda, and shots A_1, A_2, A_5, and A_8 (*A*, ATLANTIS series), fired along a line north of Bermuda, are used to check the calculated reflector positions. There are insufficient data from these shots to calculate reflector positions independently. However, excellent correspondence is obtained by matching measured travel times with those calculated to the reflector positions found from the *R-S* series (Tables 36, 37). As compared to the *R-S* series, the order of arrival is inverted in some cases for the *R* series; new echoes are recorded, while some old ones are missing; and in one case, T_1, no good match is obtained. The *A* series shows similar degrees of divergence and correspondence with the *R-S* series.

REFLECTOR POSITIONS

To calculate the reflector positions, certain basic assumptions are made. It is assumed (1) that the echo is from a single reflector and no multiple reflections are involved; (2) that the reflector is at a point, that is, it may be represented by a vertical wall from sea floor to surface, facing in that direction which will make the angle of incidence to the shot point equal to the angle of reflection to the geophone position. Furthermore, a velocity must be assigned to that part of the echo signal which is picked as the arrival, so that travel time may be translated into distance. The maximum of the echo signal is taken to correspond to the arrival of those rays which make angles with the sound channel axis from 0° to 12° and, therefore, propagate with least attenuation. The mean horizontal velocity for these rays is 4900 feet per second (Ewing and Worzel, 1948, p. 23), and accordingly this velocity is assigned to the echo signals and used in all calculations.

Given the position of shot and receiver, and the travel time of an echo from that shot, the locus of the reflector position is determined as an ellipse whose foci are the shot point and the receiver, and whose major axis is equal to the distance corresponding to the echo travel time. The intersection of the ellipses determined by several shots is at the reflector position. A line of shots which passes through the receiver gives two solutions for the reflector position, unless one solution is eliminated by a shot off the line, or by physical reasons.

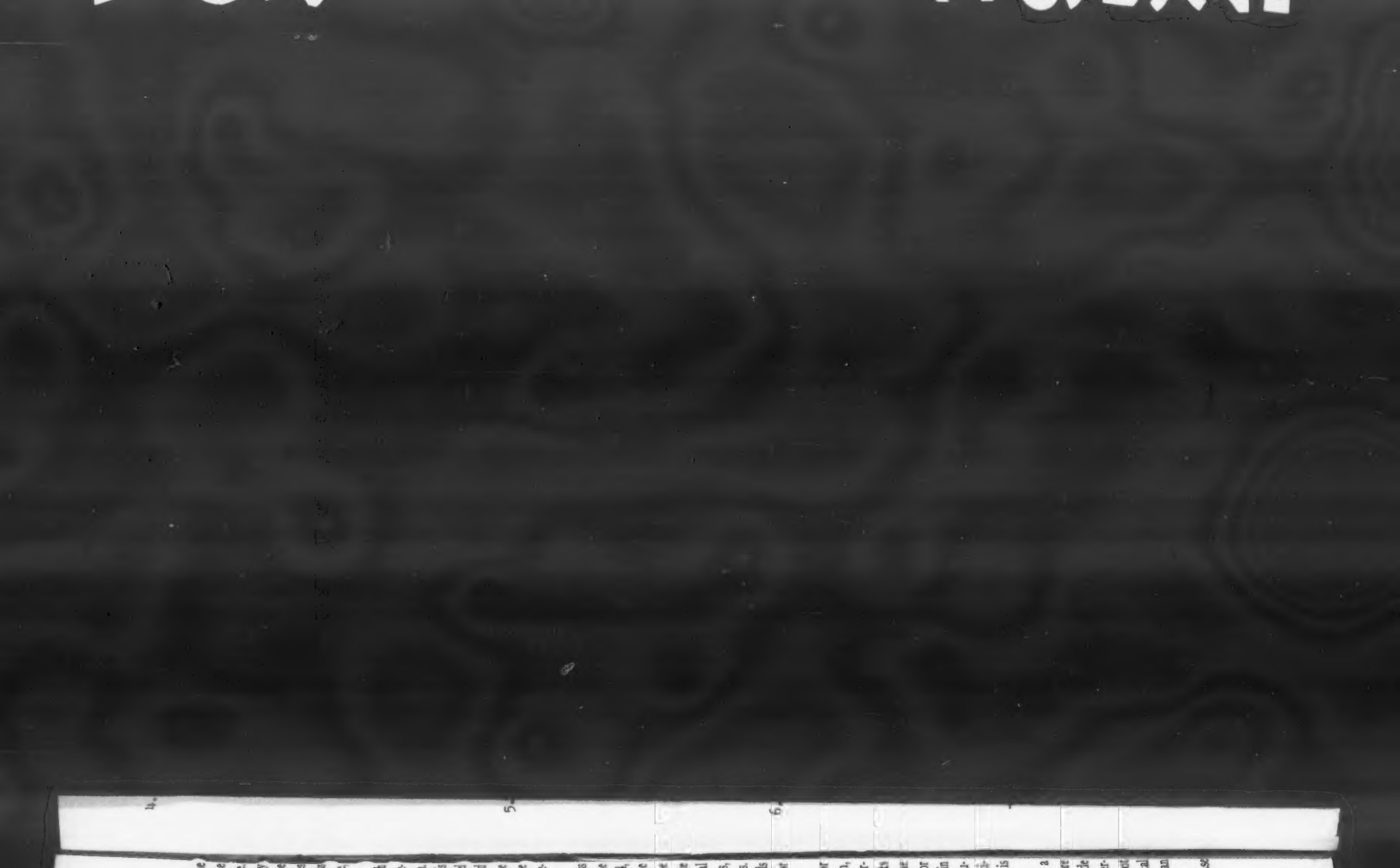
A plot of echo travel time vs. direct-path travel time for a line of shots through the receiver (Fig. 3) also gives the reflector position. The intercept of the echo line with the axis labeled "Time After Shot Instant" is the travel time for a shot directly over the receiver, and thus corresponds to twice the distance to the reflector from the receiver. The slope of the echo line is related to the azimuth of the reflector from the receiver.

For a line of shots which does not pass through the receiver position such as the REHOBOTH-SAN PABLO series *R*-195 to *S*-204, the azimuth to the reflector is indicated by the time difference between the echo travel time for shots such as *R*-195 and *S*-204. A difference of approximately 190 seconds, which is equal to the travel time between the two shot points, indicates a reflector along the line of the shots. A time difference of zero obviously corresponds to a reflector along the perpendicular bisector of the line between the shot points.

While it is possible to obtain analytical or graphical solutions for the reflector position, the formulas involved are extremely cumbersome, and the distortion of large area charts prohibits precise graphical computation. The technique used here for locating the reflector positions is to find an approximate solution in the simplest manner, and then to use this solution as the starting point for successive approximations to a more accurate answer. This is done as follows:

For the line of *C-A* shots, which provide a base line of some 800 miles, rough ellipses are swung using a string of proper length as a guide on a gnomonic projection chart. Sharp intersections are obtained if the base line from shot point to geophone is comparable to the total echo path. These intersections determine an approximate reflector position.

The line of *R-S* shots provides a short base



4. Reflector b Muir Sea Mountain 33°34' N, 62°24' W 132 miles from Geophone

Shot No.	Distance to b Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
A256	435	567	704	695	+ 9
C277	353	485	603	600	+ 3
A280	376	508	631	639	- 8
A282	362	494	614	605	+ 9
A283	354	486	604	608	- 4
C300	240	372	462	471	- 9
C301	233	365	453	456	- 3
C302	223	355	441	446	- 5
A303	252	384	477	484	- 7
A304	245	377	469	474	- 5
A305	232	364	452	455	- 3
C323	134	266	331	336	- 5
A325	148	280	347	340	+ 7
X01	126	258	321	314	+ 7

5. Reflector V* Seamount V East of Muir Sea Mountain 33°18' N, 61°40' W 159 miles from Geophone

Shot No.	Distance to V Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
C302	229	388	482	494	-12
A303	253	412	511	525	-14
A304	246	405	502	519	-17
C323	150	309	383	383	0

* There are insufficient data to locate this reflector. However, Sea Mount V is the only charted submarine structure which fits the travel time data for echo V with small deviation.

6. Reflector G* East of Muir Sea Mountain 33°22' N, 60°48' W 201 miles from Geophone

Shot No.	Distance to G Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
A256	450	651	808	809	- 1
A280	393	594	738	737	+ 1
C302	261	462	573	570	+ 3
A303	281	482	598	604	- 6
A304	274	475	590	594	- 4

* This reflector is located from Rehoboth--San Pablo Shot Data.

7. Reflector c* Sea Mount Z 32°00' N, 58°53' W 291 miles from Geophone

Shot No.	Distance to c Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
A280	381	672	834	836	- 2
C302	298	589	731	732	- 1
A303	303	594	738	735	+ 3
A304	300	591	734	729	+ 5

* There are insufficient data to locate this reflector. However, Sea Mount Z is the only charted submarine structure which fits the travel time data for echo c with small deviation.

8. Reflector d* Sea Mount Y 34°32' N, 56°45' W 414 miles from Geophone

Shot No.	Distance to d Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
C302	462	876	1087	1086	+ 1
A303	474	888	1102	1100	+ 2
A304	469	883	1096	1092	+ 4

* There are insufficient data to locate this reflector. However, Sea Mount Y is the only charted submarine structure which fits the travel time data for echo d with small deviation.

9a. Reflector e_1 Echo Bank 21°20' N, 58°50' W 727 miles from Geophone

Shot No.	Distance to e Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
A256	416	1143	1419	1451	-32
A280	458	1185	1470	1495	-25
C302	606	1333	1654	1643	+11
A303	569	1296	1608	1604	+ 4
A304	578	1305	1619	1611	+ 8
A305	592	1319	1637	1628	+ 9
A325	680	1407	1746	1711	+35

This is not considered a satisfactory solution.

9b. Reflector e_2 Caicos Island 22°02' N, 71°00' W 707 miles from Geophone

Shot No.	Distance to e_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
A256	462	1169	1451	1451	0
A280	501	1208	1499	1495	+ 4
C302	608	1315	1632	1643	-11
A303	588	1295	1607	1604	+ 3
A304	594	1301	1614	1611	+ 3
A305	605	1312	1628	1628	0
A325	680	1387	1722	1711	+11

10. Reflector f Navidad Bank 20°22' N, 68°39' W 751 miles from Geophone

Shot No.	Distance to f Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
A145	179	930	1154	1150	+ 4
C159	124	875	1086	1081	+ 5
A160	103	854	1060	1065	- 5
A161	107	858	1065	1072	- 7
C220	298	1049	1302	1289	+13
C221	307	1058	1313	1298	+15
A254	428	1179	1463	1477	-14
A255	433	1184	1469	1478	- 9
A256	442	1193	1480	1490	-10
C257	419	1170	1452	1464	-12
C258	424	1175	1458	1471	-13
C259	428	1179	1463	1476	-13
C260	434	1185	1470	1480	-10
C277	522	1273	1579	1583	- 4
C278	530	1281	1589	1590	- 1
C279	536	1287	1597	1595	+ 2
A280	494	1245	1545	1555	-10
A282	506	1257	1560	1556	+ 4
A283	512	1263	1568	1573	- 5
C300	618	1369	1699	1684	+15
C301	625	1376	1708	1701	+ 7
C302	636	1387	1722	1711	+11
A303	607	1358	1686	1682	+ 4
A304	614	1365	1694	1681	+13
A305	627	1378	1711	1710	+ 1
C323	727	1478	1835	1834	+ 1
A325	715	1466	1819	1808	+11

11. Reflector g Virgin Islands 18°52' N, 64°53' W 809 miles from Geophone

Shot No.	Distance to g Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
A145	113	922	1144	1154	-10
C159	102	911	1131	1140	- 9
A160	120	929	1153	1146	+ 8
A161	117	926	1149	1145	+ 4
C220	253	1062	1317	1319	- 2
C221	265	1074	1333	1338	- 5
A254	437	1246	1546	1545	+ 1
A255	444	1253	1555	1556	- 1
A256	456	1265	1570	1572	- 2
C257	430	1239	1538	1529	+ 9
C258	435	1244	1544	1541	+ 3
C259	440	1249	1550	1546	+ 4
C260	448	1257	1560	1553	+ 7
C277	546	1355	1682	1677	+ 5
C278	556	1365	1694	1691	+ 3
C279	563	1372	1703	1699	+ 4
A280	515	1324	1643	1641	+ 2
A282	530	1339	1662	1661	+ 1
A283	537	1346	1670	1672	- 2
C300	661	1470	1824	1821	+ 3
C301	669	1478	1835	1831	+ 4
C302	679	1488	1847	1846	+ 1
A303	645	1454	1805	1800	+55
A304	654	1463	1816	1815	+ 1
A305	669	1478	1835	1833	+ 2
C323	774	1583	1965	1973	- 8
A325	765	1574	1954	1950	+ 4

10. Reflector f Navidad Bank 20°22' N, 68°39' W 751 miles from Geophone

Shot No.	Distance to f Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
A145	179	930	1154	1150	+ 4
C159	124	875	1086	1081	+ 5
A160	103	854	1060	1065	- 5
A161	107	858	1065	1072	- 7
C220	298	1049	1302	1289	+13
C221	307	1058	1313	1298	+15
A254	428	1179	1463	1477	-14
A255	433	1184	1469	1478	- 9
A256	442	1193	1480	1490	-10
C257	419	1170	1452	1464	-12
C258	424	1175	1458	1471	-13
C259	428	1179	1463	1476	-13
C260	434	1185	1470	1480	-10
C277	522	1273	1579	1583	- 4
C278	530	1281	1589	1590	- 1
C279	536	1287	1597	1595	+ 2
A280	494	1245	1545	1555	-10
A282	506	1257	1560	1556	+ 4
A283	512	1263	1568	1573	- 5
C300	618	1369	1699	1684	+15
C301	625	1376	1708	1701	+ 7
C302	636	1387	1722	1711	+11
A303	607	1358	1686	1682	+ 4
A304	614	1365	1694	1681	+13
A305	627	1378	1711	1710	+ 1
C323	727	1478	1835	1834	+ 1
A325	715	1466	1819	1808	+11

11. Reflector g Virgin Islands 18°52' N, 64°53' W 809 miles from Geophone

Shot No.	Distance to g Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
A145	113	922	1144	1154	-10
C159	102	911	1131	1140	- 9
A160	120	929	1153	1146	+ 8
A161	117	926	1149	1145	+ 4
C220	253	1062	1317	1319	- 2
C221	265	1074	1333	1338	- 5
A254	437	1246	1546	1545	+ 1
A255	444	1253	1555	1556	- 1
A256	456	1265	1570	1572	- 2
C257	430	1239	1538	1529	+ 9
C258	435	1244	1544	1541	+ 3
C259	440	1249	1550	1546	+ 4
C260	448	1257	1560	1553	+ 7
C277	546	1355	1682	1677	+ 5
C278	556	1365	1694	1691	+ 3
C279	563	1372	1703	1699	+ 4
A280	515	1324	1643	1641	+ 2
A282	530	1339	1662	1661	+ 1
A283	537	1346	1670	1672	- 2
C300	661	1470	1824	1821	+ 3
C301	669	1478	1835	1831	+ 4
C302	679	1488	1847	1846	+ 1
A303	645	1454	1805	1800	+55
A304	654	1463	1816	1815	+ 1
A305	669	1478	1835	1833	+ 2
C323	774	1583	1965	1973	- 8
A325	765	1574	1954	1950	+ 4

12a. Reflector h_1 Northeast of Puerto Rico 18°39' N, 65°30' W 823 miles from Geophone

Shot No.	Distance to h_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
A145	123	946	1174	1185*	-11
C159	90	913	1132	1145	-13
A160	103	926	1149	1146	+ 3
A161	101	924	1147	1145	+ 2
C220	273	1096	1360	1352	+ 8
C221	286	1109	1376	1364	+12
A254	456	1279	1587	1577	+10
A255	463	1286	1595	1587	+ 8
A256	475	1298	1611	1602	+ 9
C257	449	1272	1578	1566	+12
C258	455	1278	1586	1576	+10
C259	460	1283	1592	1579	+13
C260	458	1281	1589	1587	+ 2
C277	562	1385	1719	1716	+ 3
C278	571	1394	1730	1730	0
C279	578	1401	1738	1731	+ 7
A280	530	1353	1679	1681	- 2
A282	546	1369	1699	1693	+ 6
A283	555	1378	1711	1704	+ 7
C300	678	1501	1863	1863	0
C301	686	1509	1873	1869	+ 4
C302	696	1519	1885	1889	- 4
A303	662	1485	1843	1834	+ 9
A304	671	1494	1855	1845	+10
A305	685	1508	1872	1869	+ 3
C325	797	1620	2010	2004	+ 6
A325	781	1604	1991	1988	- 7

12b. Reflector h_2 Anguilla Bank 18°43' N, 62°55' W 822 miles from Geophone

Shot No.	Distance to h_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
C220	267	1089	1351	1352	- 1
C221	278	1100	1365	1364	+ 1
A254	449	1271	1577	1577	0
A255	456	1278	1586	1587	- 1
A256	467	1289	1599	1602	- 3
C257	446	1268	1574	1566	+ 8
C258	452	1274	1581	1576	+ 5
C259	458	1280	1588	1579	+ 9
C260	465	1287	1597	1587	+10
C277	556	1378	1711	1716	- 5
C278	566	1388	1723	1730	- 7
C279	573	1395	1731	1731	0
A280	525	1347	1672	1681	- 9
A282	540	1362	1690	1693	- 3
A283	548	1370	1700	1704	- 4
C300	674	1496	1857	1863	- 6
C301	682	1502	1864	1869	- 5
C302	693	1515	1880	1889	- 9
A303	656	1478	1835	1834	+ 1
A304	665	1487	1846	1845	+ 1
A305	680	1502	1864	1869	- 5
C323	784	1606	1993	2004	-11
A325	778	1600	1986	1988	- 2

13a. Reflector i_1 North Coast of Puerto Rico 18°32' N, 66°40' W 837 miles from Geophone

Shot No.	Distance to i_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
A145	148	985	1222	1226*	- 4
C159	89	926	1149	1149	+ 4
A160	83	920	1142	1146	- 4
A161	85	922	1144	1145	- 1
C220	301	1138	1413	1419	- 6
C221	313	1150	1427	1426	+ 1
A254	475	1312	1628	1626	+ 2
A255	482	1319	1637	1633	+ 4
A256	492	1329	1649	1646	+ 3
C257	466	1303	1617	1615	+ 2
C258	472	1309	1624	1628	- 4
C259	478	1315	1632	1630	+ 2
C260	484	1321	1639	1632	+ 7
C277	580	1417	1758	1758	0
C278	589	1426	1769	1771	- 2
C279	595	1432	1777	1778	- 1
A280	550	1387	1722	1718	+ 4
A282	564	1401	1738	1743	- 5
A283	570	1407	1746	1751	- 5
C300	703	1540	1911	1903	+ 7
C301	710	1547	1920	1915	+ 5
C302	721	1558	1934	1929	+ 5
A303	678	1515	1880	1879	+ 1
A304	697	1534	1904	1894	+10
A305	711	1548	1921	1912	+ 9
C323	810	1647	2044	2050	- 6
A325	798	1635	2028	2034	- 6

13b. Reflector i_2 Anguilla Bank 18°25' N, 62°15' W 842 miles from Geophone

Shot No.	Distance to i_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
A145	288	1070	1327	1226*	- 5
C220	297	1139	1414	1419	- 5
C221	308	1150	1427	1426	+ 1
A254	462	1304	1618	1626	- 8
A255	469	1311	1627	1633	- 6
A256	480	1322	1640	1646	- 6
C257	459	1301	1614	1615	- 1
C258	465	1307	1622	1628	- 6
C259	471	1313	1629	1630	- 1
C260	478	1320	1638	1632	+ 6
C277	578	1420	1762	1758	+ 4
C278	588	1430	1774	1771	+ 3
C279	595	1437	1783	1778	+ 5
A280	547	1389	1724	1718	+ 6
A282	562	1404	1742	1743	- 1
A283	570	1412	1752	1751	+ 1
C300	696	1538	1909	1903	+ 6
C301	704	1546	1918	1915	+ 3
C302	715	1557	1932	1929	+ 3
A303	678	1520	1886	1879	+ 7
A304	687	1529	1897	1894	+ 3
A305	702	1544	1916	1912	+ 4
C323	805	1647	2044	2050	+ 6
A325	799	1641	2036	2034	+ 2

13a. Reflector i_1 North Coast of Puerto Rico $18^{\circ}32'$ N, $66^{\circ}40'$ W 837 miles from Geophone

Shot No.	Distance to i_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
A145	148	985	1222	1226*	- 4
C159	89	926	1149	1149	+ 4
A160	83	920	1142	1146	- 4
A161	85	922	1144	1145	- 1
C220	301	1138	1413	1419	- 6
C221	313	1150	1427	1426	+ 1
A254	475	1312	1628	1626	+ 2
A255	482	1319	1637	1633	+ 4
A256	492	1329	1649	1646	+ 3
C257	466	1303	1617	1615	+ 2
C258	472	1309	1624	1628	- 4
C259	478	1315	1632	1630	+ 2
C260	484	1321	1639	1632	+ 7
C277	580	1417	1758	1758	0
C278	589	1426	1769	1771	- 2
C279	595	1432	1777	1778	- 1
A280	550	1387	1722	1718	+ 4
A282	564	1401	1738	1743	- 5
A283	570	1407	1746	1751	- 5
C300	703	1540	1911	1903	+ 7
C301	710	1547	1920	1915	+ 5
C302	721	1558	1934	1929	+ 5
A303	678	1515	1880	1879	+ 1
A304	697	1534	1904	1894	+10
A305	711	1548	1921	1912	+ 9
C323	810	1647	2044	2050	- 6
A325	798	1635	2028	2034	- 6

13b. Reflector i_2 Anguilla Bank $18^{\circ}25'$ N, $62^{\circ}15'$ W 842 miles from Geophone

Shot No.	Distance to i_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
A145	288	1070	1327	1226*	- 5
C220	297	1139	1414	1419	- 5
C221	308	1150	1427	1426	+ 1
A254	462	1304	1618	1626	- 8
A255	469	1311	1627	1633	- 6
A256	480	1322	1640	1646	- 6
C257	459	1301	1614	1615	- 1
C258	465	1307	1622	1628	- 6
C259	471	1313	1629	1630	- 1
C260	478	1320	1638	1632	+ 6
C277	578	1420	1762	1758	+ 4
C278	588	1430	1774	1771	+ 3
C279	595	1437	1783	1778	+ 5
A280	547	1389	1724	1718	+ 6
A282	562	1404	1742	1743	- 1
A283	470	1412	1752	1751	+ 1
C300	696	1538	1909	1903	+ 6
C301	704	1546	1918	1915	+ 3
C302	715	1557	1932	1929	+ 3
A303	678	1520	1886	1879	+ 7
A304	687	1529	1897	1894	+ 3
A305	702	1544	1916	1912	+ 4
C323	805	1647	2044	2050	+ 6
A325	799	1641	2036	2034	+ 2

14. Refle

Shot No.
A256
C277
C278
C279
A280
A282
A283
C300
C301
C302
A303
A304
A305
C323
A325

14. Reflector 1 Guadeloupe 16°32' N, 60°40' W 972 miles from Geophone

Shot No.	Distance to j Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
A256	623	1595	1980	1983	- 3
C277	708	1680	2085	2081	+ 4
C278	718	1690	2097	2094	+ 3
C279	725	1697	2106	2104	+ 6
A280	678	1650	2047	2044	+ 3
A282	693	1665	2066	2066	0
A283	700	1672	2075	2074	+ 1
C300	824	1796	2229	2226	+ 3
C301	832	1804	2239	2238	+ 1
C302	843	1815	2253	2253	0
A303	806	1778	2207	2200	+ 7
A304	816	1788	2219	2212	+ 7
A305	830	1802	2236	2232	+ 4
C323	931	1903	2362	2370	- 8
A325	926	1898	2358	2352	+ 4

line, son
very flat
the inte
then, th
reflector
differenc
and S-2
found fo
brated i
succeedi
easily d
between
possible
proxima
The f
approxi
calculati
the refl
echo pa
travel t
travel t
travel t
adjusted
from th
mately
are some
admit re
Since
accurate
fically m
measure
cases as
adequat
within
proxima
spread
onds. In
less; in
The c
assigned
may be
without
the choi
flector p
merely
mount,
keep sl
Northea
by abou
which is
still n
are.

line, some 300 miles, and thus the ellipses are very flat for echoes with long travel times, and the intersections are poorly defined. Here, then, the azimuth from the line of shots to the reflector, as determined by the travel-time difference for the same echo from shots *R*-195 and *S*-204 is used. After several reflectors are found for the *R-S* shots, the azimuth is calibrated in terms of their time difference, and succeeding reflector positions are thus more easily determined. The point of intersection between a line drawn along the azimuth and a possible reflecting structure is taken as an approximate reflector position.

The final solutions are made by successive approximations based on great-circle distance calculations. Using the approximate position of the reflector, the great-circle distances of the echo paths are calculated, translated into travel time, and compared to the measured travel time. The position of the reflector is adjusted until the deviations of the calculated from the measured travel time are approximately a minimum. The calculations involved are somewhat tedious but are simply made and admit readily of systematization.

Since the shot positions are believed to be accurate to 2 miles, the reflector position physically may cover a considerable area, and the measured travel time may be varied in many cases as much as 10 seconds, it is considered adequate here to obtain a solution good within a 10-mile radius circle. Thus the approximation process is continued until the spread of the deviations is less than 24 seconds. In most cases, the spread is considerably less; in a few cases, slightly more.

The choice of 4900 feet per second velocity assigned to the echo signals is not critical and may be varied as much as ±50 feet per second without affecting the results significantly. For the choice of velocity at either extreme, a reflector position identified with a seamount is merely moved to another part of the same seamount, a reflector position identified with a steep slope of the islands surrounding the Northeastern Caribbean is moved north or south by about 10 miles, and a symmetrical solution which is rejected also moves about 10 miles and is still not identifiable with any charted structure.

The solutions for reflector positions are presented in Tables 4–14 for the *C-A* and Tables 15–35 for the *R-S* series.

The first echo of the *C-A* series, *b*, appears in records of 14 shots. Only shot *A*-256, the biggest shot of the group 254–260, echoes from reflector *b*. No shots farther away from Bermuda than *A*-256 produced an echo *b*. Reflector *b* corresponds to the Muir Sea Mountain, a well-known submarine structure to the northeast of Bermuda. It extends over a considerable area, and its peak is charted at 750 fathoms (Tolstoy, 1951).

Echo *V*, the second to arrive, appears only on records of four shots, all close to Bermuda, three of which are large charges. This echo fits, with small deviation, a position on a small seamount to the southeast of the Muir Sea Mountain whose peak is charted at 1120 fathoms.

Echo *G*, received on five of the big shots of the *C-A* series, does not fit any charted structure. This echo, also received from the *R-S* shots, apparently comes from a previously undiscovered seamount. A fuller discussion is given below.

Echoes *c* and *d*, also received only from three or four of the bigger shots close to Bermuda, apparently come from seamounts *Z* and *Y*, to the east and northeast of Bermuda, respectively. The minimum soundings on these seamounts are 1270 and 1074 fathoms, respectively, but detailed surveys have not been made over either. Observed reflections suggest that these seamounts are much higher.

Echo *e* appears on records of seven shots. Only the largest shots of two groups, *A*-256 and *A*-280, give this echo. This is the first echo to appear in order of travel time for which travel time increases as shot distance to the receiver decreases. The reflector which fits *e* travel times, e_2, is just north of Caicos Island in the Bahamas. Whereas the previous echoes discussed, *b*, *V*, *G*, *c*, and *d*, might not appear on records until the total path becomes short, the angle of incidence is evidently the controlling factor in this case. The only charted structure close to a symmetrical solution for *e* travel times is Echo Bank. This seamount, despite its name and the fact that its peak is charted at 34 fathoms, is about 100 miles west of a position which fits the travel-time data. The existence of Echo

Bank was already in doubt since an echo-sounding net made by R/V ATLANTIS in 1950 showed no sign of it.

Echo *f* is the first of a group of four echoes which appear on records of all the *C-A* shots. Reflector *f* is located at the Navidad Bank, which is north of Hispaniola and peaks at 8 fathoms. The Navidad Bank has a very steep gradient, rising 2500 fathoms in approximately 10 miles. No symmetrical solution is found for *f*, since the echo arrivals from shots *A*-145, *C*-159, *A*-160, and *A*-161, which are considerably off the line of the other shots, clearly fit the travel-time data.

Echo *g* is correlated with reflector *g* north of the Virgin Islands. This reflector is along the line of all the *C-A* shots except the four mentioned above. In the case of shots *C*-159, *A*-160, *A*-161, the records show a very long signal of high amplitude which appears to be the result of several simultaneous arrivals.[1] This signal is picked as the arrival of echoes *g*, *h*, and *i*. Reflectors *h* and *i* may have two solutions one to the east and one to the west of reflector position *g*. These are labeled h_1 and h_2, i_1 and i_2. Shot *A*-145 is the only one which gives two arrivals after the one correlated as *i*. These arrivals correspond with reflector positions h_2 and i_2. Shots *C*-159 and *A*-160, give no arrivals which echoes from these positions. However, the angle of incidence to these positions from the three shots is probably extremely unfavorable for a receiver at Bermuda, and thus these solutions cannot be rejected. All these reflector positions are in the vicinity of the Virgin Islands and Anguilla Bank.

Echo *j* arrives with travel times from 34 to 40 minutes. Reflector *j* is located in the vicinity of a very steep submarine slope east of Guadeloupe. The shots south of *A*-256 except *C*-220, 221, for which echo *j* does not appear, have great-circle paths to *j* which are interrupted by shoal or land areas.

The first echo of the *R-S* series, *B*, arrives some 20 seconds after the direct-path signal. It is identified with a steep bank which rises to 750 fathoms 20 miles north of Bermuda.

[1] Recordings of these shots made on board R/V ATLANTIS and CARYN showed a strong reverberation lasting more than 30 seconds, which was interpreted as being due to the confinement of a great deal of sound energy in the Puerto Rico trough (Ewing, personal communication).

The next four echoes, *C*, *D*, *E*, and *F*, all appear to reflect from the Muir Sea Mountain, *F* coinciding with *b*. Tolstoy (1951) shows in a detailed survey of the Muir Sea Mountain that there are actually two peaks, one at 755 fathoms (between *E* and *F*) and one at 845 fathoms (between *C* and *D*). There are evidently four surfaces on the Muir Sea Mountain which satisfy the conditions of reflection.

Echo *V* appears only on the records of four *R-S* shots. Reflector *V*, the seamount southeast of the Muir Sea Mountain, fits the travel-time data of these shots, four *C-A* shots, and, as will be shown, the three *R* series shots. Reflector *V* apparently lies in the shadow of the Muir Sea Mountain for the *R-S* shots. However, the rays can diffract around this obstacle (Ewing *et al.*, 1946). It is significant that the only shots for which echo *V* is not heard are the two, *R*-195, *S*-196, which are closest to the obstacle, and one, *R*-201, which is farther away but more directly in line with the seamount and reflector *V*.

If we subtract the travel times of *C*, *D*, *E*, or *F* from that of echo *G* for each shot, we obtain a constant. Therefore, *G* must lie along the same line as these reflectors and the line of the shots. The position of *G*, at 33° 22′ North Latitude and 60° 48′ West Longitude, which fits the travel-time data, does not coincide with any charted submarine structure. The travel times of echo *G* from the *C-A* shots correlate well with this position. An excellent match is obtained from the three *R* series shots which are very close to this position. The possibility of a multiple reflection which fits the data has been taken into account. For this case, the first reflection is from a position like *F*, since the azimuth criterion of travel-time differences must be satisfied. A second reflector would then lie on an ellipse whose major axis is 180 seconds long (*G–F* travel time) and whose foci are *F* and the receiver. A good part of this ellipse lies beyond the cut-off, and most of the remaining part is in an area where a reflecting structure would have given a direct echo from most of the shots studied here. Possibly an uncharted structure lies to the southeast of Bermuda in that position in which Bermuda shadows the *R-S* and *A* series shots. However, no echoes from such a position are observed from shots *C*-323 or *A*-325.

15. Reflector B Shoal Area North of Bermuda 32°43' N, 64°31' W 23 miles from Geophone

Shot No.	Distance to B Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	178	201	249	250	- 1
S196	208	231	287	287	0
R197	223	246	305	305	0
R199	254	277	343	343	0
S200	266	289	358	363	- 5
R201	283	306	379	380	- 1
S204	326	349	433	432	+ 1

16. Reflector C Muir Sea Mountain 33°50' N, 62°47' W 127 miles from Geophone

Shot No.	Distance to C Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	208	335	416	415	+ 1
S196	240	367	455	455	+ 1
R197	256	383	476	472	+ 4
R199	286	413	512	511	+ 1
S200	298	425	526	531	- 5
R201	318	445	552	551	+ 1
S204	360	487	605	604	+ 1

17. Reflector D Muir Sea Mountain 33°41' N, 62°39' W 127 miles from Geophone

Shot No.	Distance to D Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	218	345	428	427	+ 1
S196	250	377	468	467	+ 1
R197	266	393	487	486	+ 1
R199	296	423	525	526	- 1
S200	309	436	541	546	- 5
R201	329	456	566	565	+ 1
S204	370	497	617	617	0

18. Reflector E Muir Sea Mountain 33°34' N, 62°31' W 128 miles from Geophone

Shot No.	Distance to E Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	227	355	441	441	0
S196	259	387	481	479	+ 2
R197	274	402	498	498	0
R199	305	433	537	539	- 2
S200	318	446	553	559	- 6
R201	338	466	578	576	+ 2
S204	379	507	630	630	0

19. Reflector F Muir Sea Mountain 33°31' N, 62°25' W 130 miles from Geophone

Shot No.	Distance to F Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	233	363	451	450	+ 1
S196	265	395	490	490	0
R197	280	410	508	509	- 1
R199	311	441	547	548	- 1
S200	324	454	564	568	- 4
R201	343	473	587	587	0
S204	385	515	641	639	+ 2

20. Reflector G East of Muir Sea Mountain 34°54' N, 60°54' W 189 miles from Geophone

Shot No.	Distance to G Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	315	504	626	630	- 4
S196	351	540	670	669	+ 1
R197	364	553	686	687	- 2
R199	396	585	726	728	- 2
S200	409	598	743	747	- 4
R201	430	619	768	768	0
S204	470	659	818	818	0

21a. Reflector H_1 Northeast of Puerto Rico 22°34' N, 62°25' W 598 miles from Geophone

Shot No.	Distance to H_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
S196	808	1406	1744	1737	+ 7
R197	819	1417	1758	1754	+ 4
R199	840	1438	1785	1789	- 4
S200	853	1451	1801	1804	- 3
R201	864	1462	1814	1823	- 9
S204	901	1499	1861	1863	- 2

21b. Reflector H_2 Sea Mount X 34°11' N, 51°57' W 641 miles from Geophone

Shot No.	Distance to H_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
S196	753	1397	1733	1737	- 4
R197	773	1417	1758	1754	+ 4
R199	792	1436	1782	1789	- 7
S200	804	1448	1797	1804	- 7
R201	824	1468	1822	1823	- 1
S204	857	1501	1863	1863	0

22a. Reflector I_1 Caicos Island 22°10' N, 71°50' W 712 miles from Geophone

Shot No.	Distance to I_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	822	1534	1904	1908	- 4
S196	828	1540	1911	1916	- 5
R197	832	1544	1916	1919	- 3
R199	837	1549	1922	1924	- 2
S200	842	1554	1929	1929	0
R201	843	1555	1930	1932	- 2
S204	861	1573	1952	1947	+ 5

22b. Reflector I_2 South of Grand Banks 44°30' N, 56°45' W 816 miles from Geophone

Shot No.	Distance to I_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	721	1537	1907	1908	- 1
S196	723	1539	1910	1916	- 6
R197	728	1544	1916	1919	- 3
R199	736	1552	1926	1924	+ 2
S200	737	1553	1927	1929	- 2
R201	747	1563	1940	1932	+ 8
S204	752	1568	1946	1947	- 1

23a. Reflector J_1 Silver Bank 21°53' N, 71°35' W 728 miles from Geophone

Shot No.	Distance to J_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	851	1579	1960	1951	+ 9
S196	843	1571	1950	1958	- 8
R197	846	1574	1954	1963	- 9
R199	850	1578	1959	1965	- 6
S200	857	1585	1967	1972	- 5
R201	857	1585	1967	1975	- 8
S204	877	1605	1992	1985	+ 7

23b. Reflector J_2 South of Grand Banks 44°31' N, 56°08' W 829 miles from Geophone

Shot No.	Distance to J_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	741	1570	1948	1951	- 3
S196	744	1573	1952	1958	- 6
R197	748	1577	1956	1963	- 7
R199	756	1585	1968	1965	+ 3
S200	757	1586	1969	1972	- 3
R201	768	1597	1981	1975	+ 6
S204	773	1602	1938	1985	+ 3

24a. Reflector K_1 Silver Bank 21°06' N, 69°20' W 719 miles from Geophone

Shot No.	Distance to K_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	861	1580	1961	1968	- 7
S196	875	1594	1979	1980	- 1
R197	880	1599	1985	1984	+ 1
R199	890	1609	1997	1994	+ 3
S200	888	1607	1995	2000	- 5
R201	900	1619	2009	2006	+ 3
S204	926	1645	2041	2032	+ 9

24b. Reflector K_2 South of Grand Banks 42°30' N, 50°15' W 812 miles from Geophone

Shot No.	Distance to K_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	765	1577	1957	1968	-11
S196	776	1588	1971	1980	- 9
R197	783	1595	1980	1984	- 4
R199	797	1609	1997	1994	+ 3
S200	802	1614	2003	2000	+ 3
R201	815	1627	2019	2006	+13
S204	829	1641	2036	2032	+ 4

25a. Reflector L_1 Navidad Bank 20°36' N, 68°55' W 742 miles from Geophone

Shot No.	Distance to L_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	878	1620	2010	2016	- 6
S196	891	1633	2026	2031	- 5
R197	898	1640	2035	2038	- 3
R199	908	1650	2047	2051	- 4
S200	916	1658	2058	2060	- 2
R201	921	1663	2064	2063	+ 1
S204	947	1689	2096	2091	+ 5

25b. Reflector L_2 South of Grand Banks 42°30' N, 52°42' W 833 miles from Geophone

Shot No.	Distance to L_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	787	1620	2010	2016	- 6
S196	797	1630	2022	2031	- 9
R197	804	1637	2031	2038	- 7
R199	818	1651	2049	2051	- 2
S200	824	1657	2056	2060	- 4
R201	837	1670	2073	2063	+ 9

26a. Reflector M_1 Navidad Bank 20°22' N, 68°45' W 753 miles from Geophone

Shot No.	Distance to M_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	891	1644	2040	2038	+ 2
S196	904	1657	2056	2058	- 2
R197	911	1664	2065	2063	- 2
R199	922	1675	2079	2079	0
S200	929	1682	2087	2088	- 1
R201	934	1687	2094	2098	- 4
S204	960	1713	2126	2119	+ 7

26b. Reflector M_2 South of Grand Banks 42°30' N, 52°18' W 841 miles from Geophone

Shot No.	Distance to M_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	803	1644	2040	2038	+ 2
S196	813	1654	2053	2058	- 5
R197	820	1661	2061	2063	- 4
R199	834	1675	2079	2079	0
S200	840	1681	2086	2088	- 2
R201	853	1694	2103	2098	+ 5
S204	868	1709	2121	2119	+ 2

27a. Reflector N_1 Navidad Bank 19°54' N, 68°35' W 773 miles from Geophone

Shot No.	Distance to N_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	914	1687	2094	2085	+ 9
S196	928	1701	2111	2113	- 2
R197	935	1708	2120	2120	0
R199	945	1718	2133	2137	- 4
S200	954	1727	2144	2147	- 3
R201	958	1731	2148	2156	- 8
S204	985	1758	2182	2183	- 1

27b. Reflector N_2 South of Grand Banks 40°53' N, 50°33' W 846 miles from Geophone

Shot No.	Distance to N_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	835	1681	2086	2085	+ 1
S196	849	1695	2104	2113	- 9
R197	855	1701	2111	2120	- 9
R199	874	1720	2135	2137	- 2
S200	882	1728	2145	2147	- 2
R201	899	1745	2165	2156	+ 9
S204	919	1765	2190	2183	+ 7

28a. Reflector O_1 East of Hispaniola 19°11' N, 68°00' W 815 miles from Geophone

Shot No.	Distance to O_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	960	1773	2200	2198	+ 2
S196	975	1788	2219	2217	+ 2
R197	981	1794	2227	2223	+ 4
R199	994	1807	2243	2243	0
S200	1003	1816	2254	2256	- 2
R201	1007	1820	2259	2260	- 1
S204	1036	1849	2294	2295	- 1

28b. Reflector O_2 South of Grand Banks 41°30' N, 49°53' W 890 miles from Geophone

Shot No.	Distance to O_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	876	1766	2192	2198	- 6
S196	890	1780	2210	2217	- 7
R197	899	1789	2220	2223	- 2
R199	916	1806	2242	2243	- 1
S200	923	1813	2251	2256	- 5
R201	933	1828	2269	2260	+ 9
S204	956	1846	2291	2295	- 4

29a. Reflector P_1 North Coast of Puerto Rico 18°47' N, 65°15' W 816 miles from Geophone

Shot No.	Distance to P_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	984	1800	2234	2230	+ 4
S196	1004	1820	2259	2259	+ 4
R197	1012	1828	2269	2264	+ 5
R199	1028	1844	2288	2290	- 2
S200	1039	1855	2302	2304	- 2
R201	1047	1863	2312	2314	- 2
S204	1078	1894	2351	2356	- 5

29b. Reflector P_2 South of Grand Banks 40°10' N, 48°43' W 898 miles from Geophone

Shot No.	Distance to P_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	903	1801	2235	2230	+ 5
S196	920	1818	2257	2259	+ 2
R197	929	1827	2268	2264	+ 4
R199	948	1856	2290	2290	0
S200	956	1854	2301	2304	- 3
R201	973	1871	2322	2314	+ 8

22a. Reflector I_1 Caicos Island 22°10' N, 71°50' W 712 miles from Geophone

Shot No.	Distance to I_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	822	1534	1904	1908	- 4
S196	828	1540	1911	1916	- 5
R197	832	1544	1916	1919	- 3
R199	837	1549	1922	1924	- 2
S200	842	1554	1929	1929	0
R201	843	1555	1930	1932	- 2
S204	861	1573	1952	1947	+ 5

22b. Reflector I_2 South of Grand Banks 44°30' N, 56°45' W 816 miles from Geophone

Shot No.	Distance to I_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	721	1537	1907	1908	- 1
S196	723	1539	1910	1916	- 6
R197	728	1544	1916	1919	- 3
R199	736	1552	1926	1924	+ 2
S200	737	1553	1927	1929	- 2
R201	747	1563	1940	1932	+ 8
S204	752	1568	1946	1947	- 1

23a. Reflector J_1 Silver Bank 21°53' N, 71°35' W 728 miles from Geophone

Shot No.	Distance to J_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	851	1579	1960	1951	+ 9
S196	843	1571	1950	1958	- 8
R197	846	1574	1954	1963	- 9
R199	850	1578	1959	1965	- 6
S200	857	1585	1967	1972	- 5
R201	857	1585	1967	1975	- 8
S204	877	1605	1992	1985	+ 7

23b. Reflector J_2 South of Grand Banks 44°31' N, 56°08' W 829 miles from Geophone

Shot No.	Distance to J_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	741	1570	1948	1951	- 3
S196	744	1573	1952	1958	- 6
R197	748	1577	1956	1963	- 7
R199	756	1585	1968	1965	+ 3
S200	757	1586	1969	1972	- 3
R201	768	1597	1981	1975	+ 6
S204	773	1602	1988	1985	+ 3

24a. Reflector K_1 Silver Bank 21°06' N, 69°20' W 719 miles from Geophone

Shot No.	Distance to K_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	861	1580	1961	1968	- 7
S196	875	1594	1979	1980	- 1
R197	880	1599	1985	1984	+ 1
R199	890	1609	1997	1994	+ 3
S200	888	1607	1995	2000	- 5
R201	900	1619	2009	2006	+ 3
S204	926	1645	2041	2032	+ 9

24b. Reflector K_2 South of Grand Banks 42°30' N, 50°15' W 812 miles from Geophone

Shot No.	Distance to K_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	765	1577	1957	1968	-11
S196	776	1588	1971	1980	- 9
R197	783	1595	1980	1984	- 4
R199	797	1609	1997	1994	+ 3
S200	802	1614	2003	2000	+ 3
R201	815	1627	2019	2006	+13
S204	829	1641	2036	2032	+ 4

25a. Reflector L_1 Navidad Bank 20°36' N, 68°55' W 742 miles from Geophone

Shot No.	Distance to L_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	878	1620	2010	2016	- 6
S196	891	1633	2026	2031	- 5
R197	898	1640	2035	2038	- 3
R199	908	1650	2047	2051	- 4
S200	916	1658	2058	2060	- 2
R201	921	1663	2064	2063	+ 1
S204	947	1689	2096	2091	+ 5

25b. Reflector L_2 South of Grand Banks 42°30' N, 52°42' W 833 miles from Geophone

Shot No.	Distance to L_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	787	1620	2010	2016	- 6
S196	797	1630	2022	2031	- 9
R197	804	1637	2031	2038	- 7
R199	815	1651	2049	2051	- 2
S200	824	1657	2056	2060	- 4
R201	837	1670	2072	2063	+ 9

26a. Reflector M_1 Navidad Bank 20°22' N, 68°45' W 753 miles from Geophone

Shot No.	Distance to M_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	891	1644	2040	2038	+ 2
S196	904	1657	2056	2058	- 2
R197	911	1664	2065	2063	- 2
R199	922	1675	2079	2079	0
S200	929	1682	2087	2088	- 1
R201	934	1687	2094	2098	- 4
S204	960	1713	2126	2119	+ 7

26b. Reflector M_2 South of Grand Banks 42°30' N, 52°18' W 841 miles from Geophone

Shot No.	Distance to M_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	803	1644	2040	2038	+ 2
S196	813	1654	2053	2058	- 5
R197	820	1661	2061	2063	- 4
R199	834	1675	2079	2079	0
S200	840	1681	2086	2088	- 2
R201	853	1694	2103	2098	+ 5
S204	868	1709	2121	2119	+ 2

27a. Reflector N_1 Navidad Bank 19°54' N, 68°35' W 773 miles from Geophone

Shot No.	Distance to N_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	914	1687	2094	2085	+ 9
S196	928	1701	2111	2113	- 2
R197	935	1708	2120	2120	0
R199	945	1718	2133	2137	- 4
S200	954	1727	2144	2147	- 3
R201	958	1731	2148	2156	- 8
S204	985	1758	2182	2183	- 1

27b. Reflector N_2 South of Grand Banks 40°53' N, 50°33' W 846 miles from Geophone

Shot No.	Distance to N_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	835	1681	2086	2085	+ 1
S196	849	1695	2104	2113	- 9
R197	855	1701	2111	2120	- 9
R199	874	1720	2135	2137	- 2
S200	882	1728	2145	2147	- 2
R201	899	1745	2165	2156	+ 9
S204	919	1765	2190	2183	+ 7

28a. Reflector O_1 East of Hispaniola 19°11' N, 68°00' W 815 miles from Geophone

Shot No.	Distance to O_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	960	1773	2200	2198	+ 2
S196	975	1788	2219	2217	+ 2
R197	981	1794	2227	2223	+ 4
R199	994	1807	2243	2243	0
S200	1003	1816	2254	2256	- 2
R201	1007	1820	2259	2260	- 1
S204	1036	1849	2294	2295	- 1

28b. Reflector O_2 South of Grand Banks 41°30' N, 49°53' W 890 miles from Geophone

Shot No.	Distance to O_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	876	1766	2192	2198	- 6
S196	890	1780	2210	2217	- 7
R197	899	1789	2220	2223	- 2
R199	916	1806	2242	2243	- 1
S200	923	1813	2251	2256	- 5
R201	938	1828	2269	2260	+ 9
S204	956	1846	2291	2295	- 4

29a. Reflector P_1 North Coast of Puerto Rico 18°47' N, 65°15' W 816 miles from Geophone

Shot No.	Distance to P_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	984	1800	2234	2230	+ 4
S196	1004	1820	2259	2259	+ 4
R197	1012	1828	2269	2264	+ 5
R199	1028	1844	2288	2290	- 2
S200	1039	1855	2302	2304	- 2
R201	1047	1863	2312	2314	- 2
S204	1078	1894	2351	2356	- 5

29b. Reflector P_2 South of Grand Banks 40°10' N, 48°43' W 898 miles from Geophone

Shot No.	Distance to P_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	903	1801	2235	2230	+ 5
S196	920	1818	2257	2259	+ 2
R197	929	1827	2268	2264	+ 4
R199	948	1856	2290	2290	0
S200	956	1854	2301	2304	- 3
R201	973	1871	2322	2314	+ 8

30b. Reflector Q_2 South of Grand Banks 39°00' N, 47°57' W 899 miles from Geophone

Shot No.	Distance to Q_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	924	1823	2263	2262	+ 1
S196	943	1842	2285	2293	- 8
R197	944	1843	2287	2295	- 8
R199	973	1872	2323	2322	+ 1
S200	982	1881	2334	2332	+ 2
R201	1000	1899	2357	2351	+ 6
S204	1025	1924	2388	2379	+ 9

31a. Reflector R_1 East of Puerto Rico 18°30' N, 64°00' W 830 miles from Geophone

Shot No.	Distance to R_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	1005	1835	2277	2280	- 3
S196	1028	1858	2306	2308	- 2
R197	1037	1867	2317	2320	- 3
R199	1054	1884	2338	2346	- 8
S200	1066	1896	2353	2362	- 9
R201	1074	1904	2363	2367	- 4
S204	1108	1938	2406	2398	+ 8

31b. Reflector R_2 Western Mid-Atlantic Ridge 37°00' N, 47°39' W 890 miles from Geophone

Shot No.	Distance to R_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	938	1828	2269	2280	-11
S196	960	1850	2295	2308	-13
R197	972	1862	2310	2320	-10
R199	995	1885	2339	2346	- 7
S200	1006	1896	2353	2362	- 9
R201	1024	1914	2376	2367	+ 9
S204	1052	1942	2410	2398	+12

32a. Reflector S_1 Anguilla Bank 18°25' N, 62°15' W 842 miles from Geophone

Shot No.	Distance to S_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	1028	1870	2321	2322	- 1
S196	1050	1892	2349	2348	+ 1
R197	1061	1903	2362	2363	- 1
R199	1080	1922	2386	2384	+ 2
S200	1093	1935	2402	2407	- 5
R201	1103	1945	2414	2416	- 2
S204	1138	1980	2457	2451	+ 6

32b. Reflector S_2 Western Mid-Atlantic Ridge 36°00' N, 46°58' W 900 miles from Geophone

Shot No.	Distance to S_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	961	1861	2309	2322	-13
S196	985	1885	2339	2348	- 9
R197	997	1897	2354	2363	- 9
R199	1021	1921	2384	2384	0
S200	1031	1931	2397	2407	-10
R201	1051	1951	2421	2416	+ 5
S204	1086	1986	2464	2451	+13

33a. Reflector T_1 Barbuda 17°52' N, 61°40' W 882 miles from Geophone

Shot No.	Distance to T_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	1068	1950	2420	2421	- 1
S196	1091	1973	2448	2445	+ 3
R197	1102	1984	2462	2461	+ 1
R199	1122	2004	2487	2493	+ 6
S200	1134	2016	2502	2508	- 6
R201	1160	2062	2558	2562	- 4

33b. Reflector T_2 Western Mid-Atlantic Ridge 35°10' N, 46°01' W 939 miles from Geophone

Shot No.	Distance to T_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	1007	1946	2415	2421	- 6
S196	1034	1973	2449	2445	+ 4
R197	1042	1981	2459	2461	- 2
R199	1070	2009	2494	2493	+ 1
S200	1083	2022	2510	2508	+ 2
R201	1138	2077	2678	2562	+ 6

34a. Reflector U_1 Guadeloupe 16°31' N, 60°35' W 974 miles from Geophone

Shot No.	Distance to U_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	1161	2135	2650	2653	- 3
S196	1185	2159	2680	2680	0
R197	1197	2171	2694	2692	+ 2
R199	1218	2192	2720	2723	- 3
S200	1230	2204	2735	2739	- 4
R201	1241	2215	2749	2753	- 4
S204	1278	2252	2795	2794	+ 1

R201	318	445	552	551	+ 1
S204	360	487	605	604	+ 1

17. Reflector D Muir Sea Mountain 33°41' N, 62°39' W 127 miles from Geophone

Shot No.	Distance to D Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	218	345	428	427	+ 1
S196	250	377	468	467	+ 1
R197	266	393	487	486	+ 1
R199	296	423	525	526	- 1
S200	309	436	541	546	- 5
R201	329	456	566	565	+ 1
S204	370	497	617	617	0

18. Reflector E Muir Sea Mountain 33°34' N, 62°31' W 128 miles from Geophone

Shot No.	Distance to E Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	227	355	441	441	0
S196	259	387	481	479	+ 2
R197	274	402	498	498	0
R199	305	433	537	539	- 2
S200	318	446	553	559	- 6
R201	338	466	578	576	+ 2
S204	379	507	630	630	0

19. Reflector F Muir Sea Mountain 33°31' N, 62°25' W 130 miles from Geophone

Shot No.	Distance to F Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	233	363	451	450	+ 1
S196	265	395	490	490	0
R197	280	410	508	509	- 1
R199	311	441	547	548	- 1
S200	324	454	564	568	- 4
R201	343	473	587	587	0
S204	385	515	641	639	+ 2

20. Reflector G East of Muir Sea Mountain 34°54' N, 60°54' W 189 miles from Geophone

Shot No.	Distance to G Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	315	504	626	630	- 4
S196	351	540	670	669	+ 1
R197	364	553	686	687	- 2
R199	396	585	726	728	- 2
S200	409	598	743	747	- 4
R201	430	619	763	768	0
S204	470	659	818	818	0

21a. Reflector H_1 Northeast of Puerto Rico 22°34' N, 62°25' W 598 miles from Geophone

Shot No.	Distance to H_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
S196	808	1406	1744	1737	+ 7
R197	819	1417	1758	1754	+ 4
R199	840	1438	1785	1789	- 4
S200	853	1451	1801	1804	- 3
R201	864	1462	1814	1823	- 9
S204	901	1499	1861	1863	- 2

21b. Reflector H_2 Sea Mount X 34°11' N, 51°57' W 644 miles from Geophone

Shot No.	Distance to H_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
S196	753	1397	1733	1737	- 4
R197	773	1417	1758	1754	+ 4
R199	792	1436	1782	1789	- 7
S200	804	1448	1797	1804	- 7
R201	824	1468	1822	1823	- 1
S204	857	1501	1863	1863	0

S204	752	1568	1946	1947	- 1

23a. Reflector J_1 Silver Bank 21°53' N, 71°35' W 728 miles from Geophone

Shot No.	Distance to J_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	851	1579	1960	1951	+ 9
S196	843	1571	1950	1958	- 8
R197	846	1574	1954	1963	- 9
R199	850	1578	1959	1965	- 6
S200	857	1585	1967	1972	- 5
R201	857	1585	1967	1975	- 8
S204	877	1605	1992	1985	+ 7

23b. Reflector J_2 South of Grand Banks 44°31' N, 56°08' W 829 miles from Geophone

Shot No.	Distance to J_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	741	1570	1948	1951	- 3
S196	744	1573	1952	1958	- 6
R197	748	1577	1956	1963	- 7
R199	756	1585	1968	1965	+ 3
S200	757	1586	1969	1972	- 3
R201	768	1597	1981	1975	+ 6
S204	773	1602	1938	1985	+ 3

24a. Reflector K_1 Silver Bank 21°06' N, 69°20' W 719 miles from Geophone

Shot No.	Distance to K_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	861	1580	1961	1968	- 7
S196	875	1594	1979	1980	- 1
R197	880	1599	1985	1984	+ 1
R199	890	1609	1997	1994	+ 3
S200	888	1607	1995	2000	- 5
R201	900	1619	2009	2006	+ 3
S204	926	1645	2041	2032	+ 9

24b. Reflector K_2 South of Grand Banks 42°30' N, 50°15' W 812 miles from Geophone

Shot No.	Distance to K_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	765	1577	1957	1968	-11
S196	776	1588	1971	1980	- 9
R197	783	1595	1980	1984	- 4
R199	797	1609	1997	1994	+ 3
S200	802	1614	2003	2000	+ 3
R201	815	1627	2019	2006	+13
S204	829	1641	2036	2032	+ 4

25a. Reflector L_1 Navidad Bank 20°36' N, 68°55' W 742 miles from Geophone

Shot No.	Distance to L_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	878	1620	2010	2016	- 6
S196	891	1633	2026	2031	- 5
R197	898	1640	2035	2038	- 3
R199	908	1650	2047	2051	- 4
S200	916	1658	2058	2060	- 2
R201	921	1663	2064	2063	+ 1
S204	947	1689	2096	2091	+ 5

25b. Reflector L_2 South of Grand Banks 42°30' N, 52°42' W 833 miles from Geophone

Shot No.	Distance to L_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	787	1620	2010	2016	- 6
S196	797	1630	2022	2031	- 9
R197	804	1637	2031	2038	- 7
R199	818	1651	2049	2051	- 2
S200	824	1657	2056	2060	- 4
R201	837	1670	2072	2063	+ 9
S204	852	1685	2091	2091	0

S204	868	1709	2121	2119	+ 2

27a. Reflector N_1 Navidad Bank 19°54' N, 68°35' W 773 miles from Geophone

Shot No.	Distance to N_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	914	1687	2094	2085	+ 9
S196	928	1701	2111	2113	- 2
R197	935	1708	2120	2120	0
R199	945	1718	2133	2137	- 4
S200	954	1727	2144	2147	- 3
R201	958	1731	2148	2156	- 8
S204	985	1758	2182	2183	- 1

27b. Reflector N_2 South of Grand Banks 40°53' N, 50°33' W 846 miles from Geophone

Shot No.	Distance to N_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	835	1681	2086	2085	+ 1
S196	849	1695	2104	2113	- 9
R197	855	1701	2111	2120	- 9
R199	874	1720	2135	2137	- 2
S200	882	1728	2145	2147	- 2
R201	899	1745	2165	2156	+ 9
S204	919	1765	2190	2183	+ 7

28a. Reflector O_1 East of Hispaniola 19°11' N, 68°00' W 815 miles from Geophone

Shot No.	Distance to O_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	960	1773	2200	2198	+ 2
S196	975	1788	2219	2217	+ 2
R197	981	1794	2227	2223	+ 4
R199	994	1807	2243	2243	0
S200	1003	1816	2254	2256	- 2
R201	1007	1820	2259	2260	- 1
S204	1036	1849	2294	2295	- 1

28b. Reflector O_2 South of Grand Banks 41°30' N, 49°53' W 890 miles from Geophone

Shot No.	Distance to O_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	876	1766	2192	2198	- 6
S196	890	1780	2210	2217	- 7
R197	899	1789	2220	2223	- 2
R199	916	1806	2242	2243	- 1
S200	923	1813	2251	2256	- 5
R201	938	1828	2269	2260	+ 9
S204	956	1846	2291	2295	- 4

29a. Reflector P_1 North Coast of Puerto Rico 18°47' N, 65°15' W 816 miles from Geophone

Shot No.	Distance to P_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	984	1800	2234	2230	+ 4
S196	1004	1820	2259	2259	+ 4
R197	1012	1828	2269	2264	+ 5
R199	1028	1844	2288	2290	- 2
S200	1039	1855	2302	2304	- 2
R201	1047	1863	2312	2314	- 2
S204	1078	1894	2351	2356	- 5

29b. Reflector P_2 South of Grand Banks 40°10' N, 48°43' W 898 miles from Geophone

Shot No.	Distance to P_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	903	1801	2235	2230	+ 5
S196	920	1818	2257	2259	+ 2
R197	929	1827	2268	2264	+ 4
R199	948	1856	2290	2290	0
S200	956	1854	2301	2304	- 3
R201	973	1871	2322	2314	+ 8
S204	995	1893	2349	2356	- 7

30a. Reflector Q_1 Anguilla Bank 18°46' N, 63°00' W 818 miles from Geophone

Shot No.	Distance to Q_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	998	1816	2254	2262	- 8
S196	1023	1841	2284	2293	- 9
R197	1032	1850	2295	2295	0
R199	1051	1869	2319	2322	- 3
S200	1063	1881	2334	2332	+ 2
R201	1072	1890	2345	2351	- 6
S204	1107	1925	2389	2379	+10

Shot No.	Miles	Miles	Seconds	Seconds	Seconds
R195	851	1579	1960	1951	+ 9
S196	843	1571	1950	1958	- 8
R197	846	1574	1954	1963	- 9
R199	850	1578	1959	1965	- 6
S200	857	1585	1967	1972	- 5
R201	857	1585	1967	1975	- 8
S204	877	1605	1992	1985	+ 7

23b. Reflector J_2 South of Grand Banks 44°31' N, 56°08' W 829 miles from Geophone

Shot No.	Distance to J_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	741	1570	1948	1951	- 3
S196	744	1573	1952	1958	- 6
R197	748	1577	1956	1963	- 7
R199	756	1585	1968	1965	+ 3
S200	757	1586	1969	1972	- 3
R201	768	1597	1981	1975	+ 6
S204	773	1602	1938	1985	+ 3

24a. Reflector K_1 Silver Bank 21°06' N, 69°20' W 719 miles from Geophone

Shot No.	Distance to K_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	861	1580	1961	1968	- 7
S196	875	1594	1979	1980	- 1
R197	880	1599	1985	1984	+ 1
R199	890	1609	1997	1994	+ 3
S200	888	1607	1995	2000	- 5
R201	900	1619	2009	2006	+ 3
S204	926	1645	2041	2032	+ 9

24b. Reflector K_2 South of Grand Banks 42°30' N, 50°15' W 812 miles from Geophone

Shot No.	Distance to K_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	765	1577	1957	1968	-11
S196	776	1588	1971	1980	- 9
R197	783	1595	1980	1984	- 4
R199	797	1609	1997	1994	+ 3
S200	802	1614	2003	2000	+ 3
R201	815	1627	2019	2006	+13
S204	829	1641	2036	2032	+ 4

25a. Reflector L_1 Navidad Bank 20°36' N, 68°55' W 742 miles from Geophone

Shot No.	Distance to L_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	878	1620	2010	2016	- 6
S196	891	1633	2026	2031	- 5
R197	898	1640	2035	2038	- 3
R199	908	1650	2047	2051	- 4
S200	916	1658	2058	2060	- 2
R201	921	1663	2064	2063	+ 1
S204	947	1689	2096	2091	+ 5

25b. Reflector L_2 South of Grand Banks 42°30' N, 52°42' W 833 miles from Geophone

Shot No.	Distance to L_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	787	1620	2010	2016	- 6
S196	797	1630	2022	2031	- 9
R197	804	1637	2031	2038	- 7
R199	815	1651	2049	2051	- 2
S200	824	1657	2056	2060	- 4
R201	837	1670	2072	2063	+ 9
S204	852	1685	2091	2091	0

Shot No.	Miles	Miles	Seconds	Seconds	Seconds
R195	914	1687	2094	2085	+ 9
S196	928	1701	2111	2113	- 2
R197	935	1708	2120	2120	0
R199	945	1718	2133	2137	- 4
S200	954	1727	2144	2147	- 3
R201	958	1731	2148	2156	- 8
S204	985	1758	2182	2183	- 1

27b. Reflector N_2 South of Grand Banks 40°53' N, 50°33' W 846 miles from Geophone

Shot No.	Distance to N_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	835	1681	2086	2085	+ 1
S196	849	1695	2104	2113	- 9
R197	855	1701	2111	2120	- 9
R199	874	1720	2135	2137	- 2
S200	882	1728	2145	2147	- 2
R201	899	1745	2165	2156	+ 9
S204	919	1765	2190	2183	+ 7

28a. Reflector O_1 East of Hispaniola 19°11' N, 68°00' W 815 miles from Geophone

Shot No.	Distance to O_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	960	1773	2200	2198	+ 2
S196	975	1788	2219	2217	+ 2
R197	981	1794	2227	2223	+ 4
R199	994	1807	2243	2243	0
S200	1003	1816	2254	2256	- 2
R201	1007	1820	2259	2260	- 1
S204	1036	1849	2294	2295	- 1

28b. Reflector O_2 South of Grand Banks 41°30' N, 49°53' W 890 miles from Geophone

Shot No.	Distance to O_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	876	1766	2192	2198	- 6
S196	890	1780	2210	2217	- 7
R197	899	1789	2220	2223	- 2
R199	916	1806	2242	2243	- 1
S200	923	1813	2251	2256	- 5
R201	938	1828	2269	2260	+ 9
S204	956	1846	2291	2295	- 4

29a. Reflector P_1 North Coast of Puerto Rico 18°47' N, 65°15' W 816 miles from Geophone

Shot No.	Distance to P_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	984	1800	2234	2230	+ 4
S196	1004	1820	2259	2259	+ 4
R197	1012	1828	2269	2264	+ 5
R199	1028	1844	2288	2290	- 2
S200	1039	1855	2302	2304	- 2
R201	1047	1863	2312	2314	- 2
S204	1078	1894	2351	2356	- 5

29b. Reflector P_2 South of Grand Banks 40°10' N, 48°43' W 898 miles from Geophone

Shot No.	Distance to P_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	903	1801	2235	2230	+ 5
S196	920	1818	2257	2259	+ 2
R197	929	1827	2268	2264	+ 4
R199	948	1856	2290	2290	0
S200	956	1854	2301	2304	- 3
R201	973	1871	2322	2314	+ 8
S204	995	1893	2349	2356	- 7

30a. Reflector Q_1 Anguilla Bank 18°46' N, 63°00' W 818 miles from Geophone

Shot No.	Distance to Q_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	998	1816	2254	2262	- 8
S196	1023	1841	2284	2293	- 9
R197	1032	1850	2295	2295	0
R199	1051	1869	2319	2322	- 3
S200	1063	1881	2334	2332	+ 2
R201	1072	1890	2345	2351	- 6
S204	1107	1925	2389	2379	+10

Shot No.	Miles	Miles	Seconds	Seconds	Seconds
R195	938	1828	2269	2280	-11
S196	960	1850	2295	2308	-13
R197	972	1862	2310	2320	-10
R199	995	1885	2339	2346	- 7
S200	1006	1896	2353	2362	- 9
R201	1024	1914	2376	2367	+ 9
S204	1052	1942	2410	2398	+12

32a. Reflector S_1 Anguilla Bank 18°25' N, 62°15' W 842 miles from Geophone

Shot No.	Distance to S_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	1028	1870	2321	2322	- 1
S196	1050	1892	2349	2348	+ 1
R197	1061	1903	2362	2363	- 1
R199	1080	1922	2386	2384	+ 2
S200	1093	1935	2402	2407	- 5
R201	1103	1945	2414	2416	- 2
S204	1138	1980	2457	2451	+ 6

32b. Reflector S_2 Western Mid-Atlantic Ridge 36°00' N, 46°58' W 900 miles from Geophone

Shot No.	Distance to S_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	961	1861	2309	2322	-13
S196	985	1885	2339	2348	- 9
R197	997	1897	2354	2363	- 9
R199	1021	1921	2384	2384	0
S200	1031	1931	2397	2407	-10
R201	1051	1951	2421	2416	+ 5
S204	1086	1986	2464	2451	+13

33a. Reflector T_1 Barbuda 17°52' N, 61°40' W 882 miles from Geophone

Shot No.	Distance to T_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	1068	1950	2420	2421	- 1
S196	1091	1973	2448	2445	+ 3
R197	1102	1984	2462	2461	+ 1
R199	1122	2004	2487	2493	+ 6
S200	1134	2016	2502	2508	- 6
R201	1150	2032	2522	2526	- 4
S204	1180	2062	2558	2562	- 4

33b. Reflector T_2 Western Mid-Atlantic Ridge 35°10' N, 46°01' W 939 miles from Geophone

Shot No.	Distance to T_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	1007	1946	2415	2421	- 6
S196	1034	1973	2449	2445	+ 4
R197	1042	1981	2459	2461	- 2
R199	1070	2009	2494	2493	+ 1
S200	1083	2022	2510	2508	+ 2
R201	1100	2038	2530	2526	+ 4
S204	1138	2077	2678	2562	+ 6

34a. Reflector U_1 Guadeloupe 16°31' N, 60°35' W 974 miles from Geophone

Shot No.	Distance to U_1 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	1161	2135	2650	2653	- 3
S196	1185	2159	2680	2680	0
R197	1197	2171	2694	2692	+ 2
R199	1218	2192	2720	2723	- 3
S200	1230	2204	2735	2739	- 4
R201	1241	2215	2749	2753	- 4
S204	1278	2252	2795	2794	+ 1

34b. Reflector U_2 Western Mid-Atlantic Ridge 36°00' N, 44°08' W 1036 miles from Geophone

Shot No.	Distance to U_2 Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R195	1097	2133	2648	2653	- 5
S196	1121	2157	2676	2680	- 4
R197	1134	2170	2692	2692	0
R199	1157	2193	2728	2723	+ 5
S200	1168	2204	2735	2739	- 4
R201	1186	2222	2758	2753	+ 5
S204	1221	2257	2801	2794	+ 7

35. Reflector V* Sea Mount East of Muir Sea Mountain 33°18' N, 61°40' W 159 miles from Geophone

Shot No.	Distance to V Miles	Total Path Miles	Calculated Travel Time Seconds	Measured Travel Time Seconds	Deviation from Measured Travel Time Seconds
R197	317	476	591	593	- 2
R199	343	502	623	610-640	?
S200	359	518	643	630-650	?
S204	419	578	718	721	- 3

* There are insufficient data to locate this reflector. However, Sea Mount V is the only charted submarine structure which fits the travel time data for echo V, with small deviation.

nd *F*, all
fountain,
hows in a
ntain that
e at 735
he at 845
are evi-
ea Moun-
reflection.
ds of four
southeast
travel-time
s, and, as
shots. Re-
dow of the
hots. How-
his obstacle
nt that the
t heard are
osest to the
rther away
e seamount

of *C*, *D*, *E*,
shot, we ob-
ust lie along
nd the line of
3° 22′ North
gitude, which
coincide with
e. The travel
hots correlate
llent match is
hots which are
he possibility
s the data has
this case, the
n like *F*, since
ime differences
reflector would
jor axis is 180
and whose foci
od part of this
nd most of the
here a reflecting
direct echo from
re. Possibly an
he southeast of
which Bermuda
shots. However,
on are observed

In the most recent and most nearly complete summary of submarine topography of the North Atlantic, Tolstoy (1951) shows only one

The solutions sublettered *1* from I_1 through U_1 are taken to be the significant ones because: (1) None of the solutions I_2 through U_2 coincide with charted submarine structures, except perhaps T_2, which is the position of a relatively gently graded seamount whose peak is at 1440 fathoms. The solutions I_1 through U_1, on the other hand, all coincide with the steep slopes and banks of the northern side of the Bahamas and other islands surrounding the northeastern Caribbean Sea. (2) Reflector J_1 conicides with e_2, L_1 with F, P_1 with g and h_1, Q_1 with h_2, S_1 with i_2, and U_1 with j. It is significant that these are all the largest amplitude echoes from the *R-S* shots.

The reflectors found with the *R-S* echo data are checked by the two series of shots *R* and *A*.

TABLE 36—REHOBOTH-SAN PABLO SHOTS EAST OF BERMUDA

Echo	Shot R192			Shot R193			Shot R194		
	Meas. T. T. Sec.	Matches Reflector	Dev. Sec.	Meas. T. T. Sec.	Matches Reflector	Dev. Sec.	Meas. T. T. Sec.	Matches Reflector	Dev. Sec.
r_0	221	A		208	A		195	A	
r_1	239	B	− 1	224	B	− 1	210	B	− 1
r_2	239	F	−11	224	F	−14	227	F	0
r_3	239	V	0	224	V	− 6	227	V	0
r_3	[1]			252	?		251	?	
r_4	291	G	0	303	G	− 1	313	G	+ 1
r_5	365	?					384	?	
r_6	383						409	?	
r_7	529	Z	− 4				543	Z	− 8
r_8	818	Y	− 4	831	Y	− 1	844	Y	− 2
r_9	1417	X[2]	− 1				1444	X	+ 1
r_{10}	1571	W[3]	− 1				1595	W	+ 2
r_{11}	1916	K_1	− 6				1903	K_1	+ 2
r_{12}	1960	L_1	1972[4]	1950	L_1	1963	1940	L_1	1955
r_{12}	to	M_1	1992	to	M_1	1986	to	M_1	1979
r_{13}	2050	N_1	2044	2020			2040	N_1	2029
r_{13}	2081	Q_1	− 7	2079	Q_1	− 8	2078	Q_1	− 7
r_{14}	2101	P_1	− 3	2098	P_1	− 4	2095	P_1	− 5
r_{15}	2124	O_1	− 2	2115	O_1	− 5	2117	O_1	− 6
r_{15}	2124	R_1	− 5	2115	R_1	0	2117	R_1	− 3
r_{15}	2124	S_1	− 2	2115	S_1	−10	2117	S_1	+ 9
r_{16}	2139	S_1	−17	2138	S_1	−13	2136	S_1	− 8
r_{17}	2160	T_1	−55				2156	T_1	+59
r_{18}	2437	U_1	− 9	2436	U_1	− 6	2435	U_1	− 4

NOTES: (1) Amplifier blocked.
(2) Seamount *X* is at 34°11′ North Latitude, 51°39′ West Longitude; 635 miles from geophone
(3) Seamount *W* is at 34°35′ North Latitude, 50°27′ West Longitude; 718 miles from geophone.
(4) Echo r_{12} is a long drawn-out signal with no distinct maximum. The calculated travel times for reflections are given in place of deviations of calculated from measured travel time.

sounding track approaching this position, but, it did not cross it. The best conclusion is that a previously undiscovered seamount is in the vicinity of the position of reflector *G*.

Echoes *H* through *U* are correlated with two reflector positions each, those with subletter *1* lying to the south of Bermuda, those with subletter *2* to the east and north. The solutions are presented in Tables 21 through 34.

For echo *H*, H_2 is selected as the reflector, because it coincides with a known submarine structure, seamount X. In addition echoes of shots *R*-192 and *R*-194 are correlated with this seamount.

The pattern of echoes received from these series of shots cannot be correlated with those of the *C-A* and *R-S* series on the basis of signal r_7, r_8, and r_9 correlate with seamounts *X*, *Y*, and *Z*. The only possible reflector that fits r_{10} is seamount *W*, for which no other data are

TABLE 37—ATLANTIS SHOTS NORTH OF BERMUDA

Echo	Shot A_1[1]			Shot A_2			Shot A_3[2]			Shot A_4[3]		
	Meas. T. T. Sec.	Matches Reflector	Dev. Sec.	Meas. T. T. Sec.	Matches Reflector	Dev. Sec.	Meas. T. T. Sec.	Matches Reflector	Dev. Sec.	Meas. T. T. Sec.	Matches Reflector	Dev. Sec.
a_1	372	A		306	A		121	A		82	A	
a_2	387	B	+ 5	319	B	0	133	B	0	91	B	− 2
a_3	501	C	− 1	420	C	+ 2						
a_4	516	D	− 2	433	D	0						
a_5	527	E	− 1	447	E	− 3						
a_6	527	F	+ 8	462	F	0	319	F	+ 2	297	F	+ 2
a_7	885	?										
a_8				1325	?							
a_9				Recorder Inoperative			1854	?				
a_9	2108	J_1	− 5				1900[4]	J_1	1909			
a_9	2108	K_1	+ 9				to	K_1	1902			
a_{10}	2175	L_1	+ 3				2010	L_1	1959	1925	L_1	0
a_{11}								M_1	1987			
a_{12}							2141	O_1	− 6			
a_{13}										2184	S_1	− 2
a_{14}	2390	P_1	+ 8									
a_{15}	2430	Q_1	−13									
a_{16}	2430	R_1	+12									
a_{17}							2548	U_1	− 1	2507	U_1	− 2

NOTES: (1) The great-circle path from Shot A_1 tangent to 100 fathom line at Bermuda "shadows" *Q*, *S*, *T*, *U*.

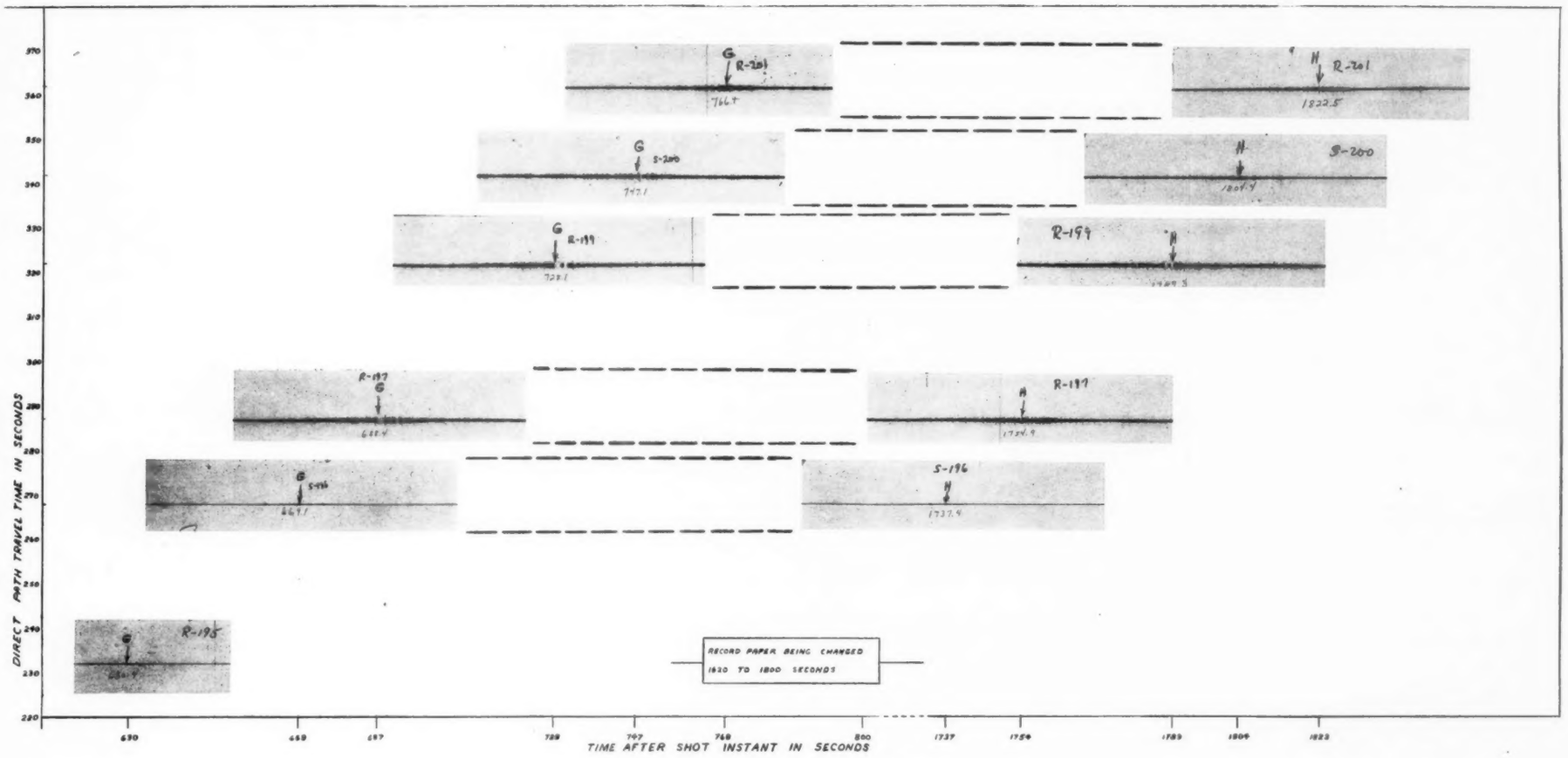
(2) See Note 1. Shadowed for Shot A_3: *P*, *Q*, *R*, *S*, *T*.

(3) See Note 1. Shadowed for Shot A_4: *N*, *O*, *P*, *Q*, *R*.

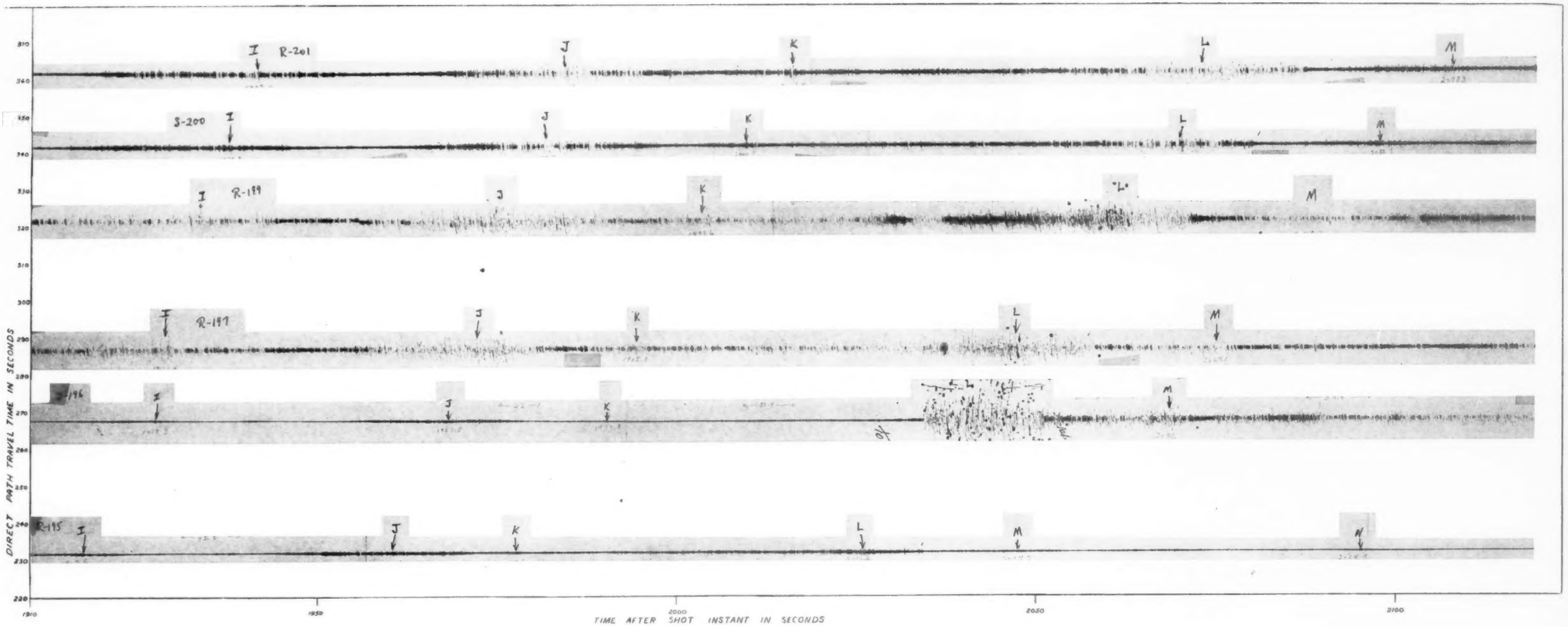
(4) Echo a_9–a_{10} is a long drawn-out signal with no distinct maximum. The calculated travel times for reflections are given in place of deviations of calculated from measured travel times.

character and relative travel time. The theoretical travel times for these shots, including all the reflectors found, were calculated (Tables 36, 37). The *R* series produced echoes r_1 and r_2 which correspond with reflectors *B*, *F*, and *V*. Echo r_2 is a better match for *V* than for *F*, and it is possible that only shot *R*-194, for which theoretical *F* and *V* travel times have no deviation from the measured travel time, can obtain a favorable angle of incidence with reflector *F*. Echo r_3 is highly questionable and does not correlate with any known reflector. This is also true of echoes r_5 and r_6, which are included only for the sake of completeness. Echo r_4, an excellent echo signal, correlates well with the position of *G* found from the *R-S* data. Echoes

available. Note that *R*-193, a partial detonation, echoed significantly only from seamount *Y*. The series of echoes r_{11} to r_{18} are late arrivals with travel times from 32 to 40 minutes. These correlate with the reflectors found bordering the Caribbean. Echo r_{12} is a very long signal of high amplitude in every case and corresponds to the simultaneous arrival of reflections from L_1, M_1, and N_1. Good correlation is also obtained with reflectors O_1, P_1, Q_1, R_1, S_1, and U_1. The difference of the order of arrival with respect to the *R-S* shots indicated by Table 36 is as expected from the position of the *R* series shots. Echo r_{17} is evidently too late for S_1 and much too early for T_1. Similarly, echo r_{18} does not match reflector S_1 too well. Consid-



ECHOES OF REHOBOTH - SAN PABLO SHOTS



ECHOES OF REHOBOTH - SAN PABLO SHOTS

ering
r_{16} a
secon
evide
shott
quite
R-S
of th
reflec
flecte
Th
spon
A_1 a
the
paren
flect
It is
critic
whic
with
cut-o
run b
Ec
whic
A_5 r
relat
feren
to ar
Ec
reflec
patte
the s
the r
In ev
are o
Th
(1)
recei
predo
50 cy
miles
indic
(2)
relati
follo
to th
the r
(a)
nal i
make

ering that the travel-time difference of echoes r_{16} and r_{17} from shot *R*-192 to shot *R*-194 is 4 seconds or less, the azimuth of the reflector is evidently due north or south of the line of shots. Considering that the incidence angle is quite different for these shots from that for the *R-S* or *C-A* shots, it is probable that some part of the area of steep submarine slopes between reflector S_1 and U_1, other than T_1, is the reflector for echoes r_{16} and r_{17}.

The *A* series produced echoes which correspond with reflectors *B*, *C*, *D*, *E*, and *F*. Shots A_1 and A_2 give echoes which correspond with the *R-S* shots, whereas A_3 and A_4 reflect apparently only from *F*. The *C-A* shots also reflect only from *b* which coincides with *F*. It is evident, therefore, that there is some critical azimuth from the Muir Sea Mountain which is a cut-off for reflectors *C*, *D*, and *E* with respect to the Bermuda receiver. This cut-off line for *C*, *D*, and *E* reflections must run between shots A_3 and shot *R*-195.

Echoes a_6, a_7 and a_8 are good echo signals which appear on records of shots A_1, A_2, and A_3 respectively. They cannot possibly be correlated with each other since their time differences exceed the travel time from one shot to another.

Echoes a_9 through a_{16} are correlated with the reflector positions already known. The echo pattern from shot to shot changes greatly since the shadow cast by Bermuda with respect to the reflectors to the south varies considerably. In every case, however, consistent correlations are obtained with the previous results.

Conclusions

The work presented here shows the following:

(1) Submarine echoes of explosive sound are received which have little character and are of predominantly low-frequency content (5 to 50 cycles per second). A range of at least 2000 miles over the total path for a 50-pound shot is indicated for these sounds.

(2) The echoes are correlated on the basis of relative arrival time and signal character. The following assumptions are made with respect to the properties of the signal, the path, and the reflector:

(a) The maximum-amplitude part of the signal is assumed to correspond to the rays which make angles from 0–12° with the sound-channel

Table 38—List of Known Reflectors

	Latitude North	Longitude West
b	33° 34′	62° 24′
c	32° 00′	58° 53′
d	34° 32′	56° 45′
e_1	21° 20′	58° 50′
e_2	22° 02′	71° 00′
f	20° 22′	68° 39′
g	18° 52′	64° 53′
h_1	18° 39′	65° 30′
h_2	18° 43′	62° 55′
i_1	18° 39′	67° 20′
i_2	18° 25′	62° 15′
j	16° 32′	60° 40′
B	32° 43′	64° 31′
C	33° 50′	62° 47′
D	33° 41′	62° 39′
E	33° 34′	62° 31′
F	33° 31′	62° 25′
G	33° 22′	60° 48′
H_2	34° 11′	51° 57′
I_1	22° 10′	71° 50′
J_1	21° 53′	71° 35′
K_1	21° 06′	69° 20′
L_1	20° 36′	68° 55′
M_1	20° 22′	68° 45′
N_1	19° 54′	68° 35′
O_1	19° 11′	68° 00′
P_1	18° 47′	65° 15′
Q_1	18° 46′	63° 00′
R_1	18° 30′	64° 00′
S_1	18° 25′	62° 15′
T_1	17° 52′	61° 40′
U_1	16° 31′	60° 35′
V	33° 18′	61° 40′
W	34° 35′	50° 27′
X	34° 11′	51° 39′
Y	34° 32′	56° 45′
Z	32° 00′	58° 53′
List of Symmetrical Solutions		
H_4	22° 34′	62° 25′
I_2	44° 30′	56° 45′
J_2	44° 31′	56° 08′
K_2	42° 30′	50° 15′
L_2	42° 30′	52° 42′
M_2	42° 30′	52° 18′
N_2	50° 53′	50° 33′
O_2	41° 30′	49° 53′
P_2	40° 10′	48° 43′
Q_2	39° 00′	47° 57′
R_2	37° 00′	47° 39′
S_2	36° 00′	46° 58′
T_2	35° 10′	46° 01′
U_2	36° 00′	44° 08′

axis and are least attenuated. Accordingly a velocity of 4900 feet per second, which is the mean horizontal velocity of these rays in a typical Atlantic Ocean path, is assigned to the echo sound.

(b) The path of an echo sound is assumed to include only one reflection.

(c) For purposes of calculating its position, the reflecting structure is idealized so that reflection is assumed to take place at a point.

(3) In every case but one, the echoes are correlated with known submarine structures having steep gradients. Most of these structures are the steep submarine slopes of the islands surrounding the northeastern part of the Caribbean Sea. The Muir Sea Mountain and several seamounts to the east of Bermuda are reflectors of other echoes received. The positions of the known reflectors are shown in Plate 1 and labeled b, c, d, e_2, f, g, h_1, h_2, i_1, i_2, j, B, C, D, E, F, H_2, I_1, J_1, K_1, L_1, M_1, N_1, O_1, P_1, Q_1, R_1, S_1, T_1, U_1, V, W, X, Y, and Z. An uncharted structure, labeled *G*, is indicated to be in the vicinity of 33° 22′ North Latitude, 60° 48′ West Longitude. The positions of all the solutions for reflector positions are listed in Table 38.

Echo signals may be used very efficiently to chart large areas of submarine topography. It is suggested that a properly equipped ship, utilizing sound-channel echo-ranging technique, could explore an area of thousands of square miles in a very short time, and probably locate every significant submarine structure which rises to within 1000 fathoms of the surface.

References Cited

Ewing, M., and Worzel, J. L., (1948) *Long-range sound transmission*, in Ewing, Maurice; Worzel, J. L., and Pekeris, C. L., *Propagation of sound in water*, Geol. Soc. Am., Mem. 27, p. 1–35.

——, Press, F., and Worzel, J. L., (1951) *Further study of the T-phase*, Seismol. Soc. Am., Bull., vol. 42, p. 37–51.

——, Woollard, G. P., Vine, A. C., and Worzel, J. L., (1946) *Recent results in submarine geophysics*, Geol. Soc. Am., Bull., vol. 57, p. 904–934.

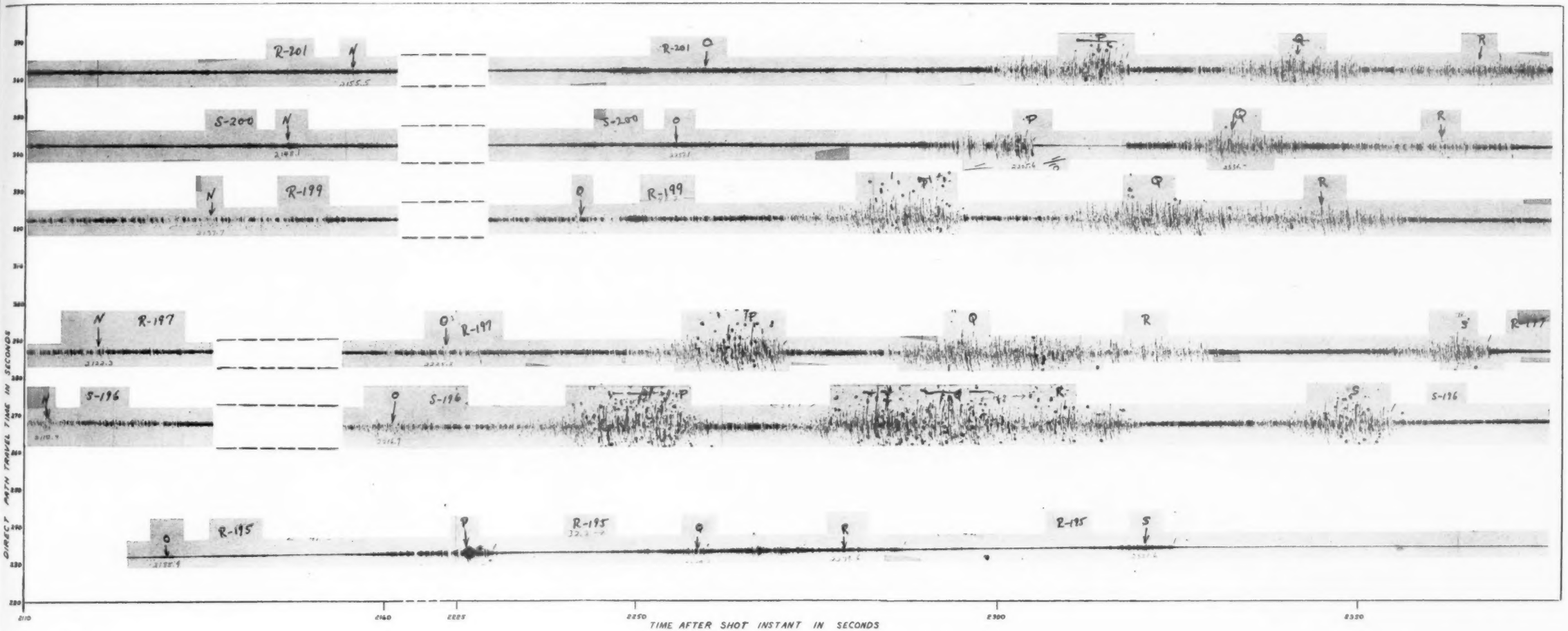
Tolstoy, I., (1951) *Submarine topography in the North Atlantic*, Geol. Soc. Am., Bull., vol. 62, p. 441–450.

——, and Ewing, M., (1950) *The T-phase of shallow focus earthquakes*, Seismol. Soc. Am., Bull., vol. 40, p. 25–51.

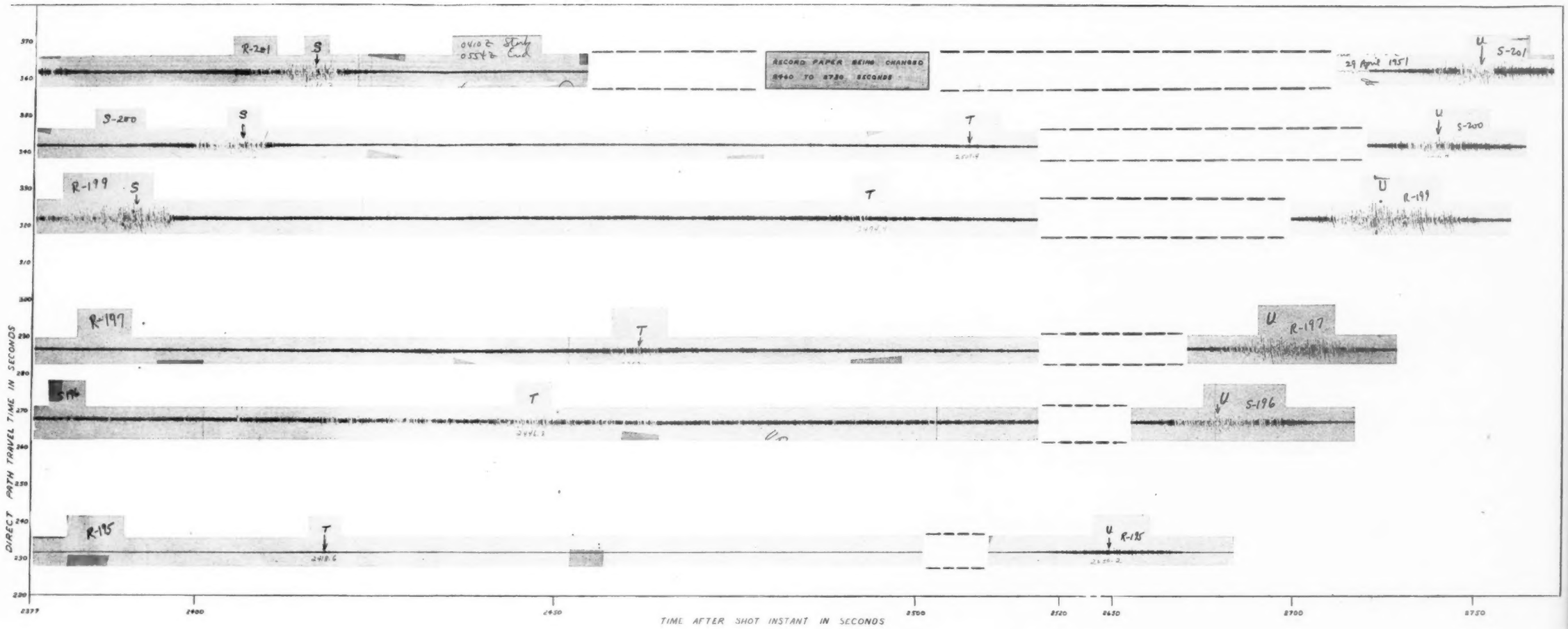
Lamont Geological Observatory, Palisades, New York.

Manuscript Received by the Secretary of the Society, November 21, 1951.

Lamont Geological Observatory Contribution No. 63.



ECHOES OF REHOBOTH - SAN PABLO SHOTS



ECHOES OF REHOBOTH - SAN PABLO SHOTS

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 63, PP. 1069-1072 OCTOBER 1952

Short Notes

OUR SHRINKING GLOBE—A DISCUSSION

BY K. O. EMERY AND M. L. NATLAND

In a recent paper, Dr. K. K. Landes (1952) expressed a number of views to which the writers take exception. Most of the evidence bearing on these matters is given in articles cited by him, but some had not been published when his paper was written, though it was generally known among marine geologists. Lack of this latter fund of knowledge makes it difficult for a man not actively working in the rapidly advancing field of submarine geology to write effectively about it. In the fear that his article may exert too great an influence on the uninformed reader, we believe it advisable to discuss certain features more fully.

We do not propose to challenge the geological possibility of the sinking of about a third of a billion cubic miles of sea floor on a contracting earth core followed by sinking of the continents, associated with several smaller cycles of sinking, all during small parts of the Pleistocene Epoch. Others are more able to cope with that problem than we are. However, we do question whether even such huge crustal movements, causing (according to Landes) a lowering of sea level of 13,300 feet, would help to explain known characteristics of submarine canyons, guyots, and deep-sea sands.

Even if sea level dropped 13,300 feet, the lower parts of all submarine canyons would not be exposed as Landes himself pointed out. Hudson Canyon is known to extend to depths of about 14,400 feet (Ericson, Ewing, and Heezen, 1952) and very likely is not unique in that respect. According to Landes' thesis the outer portion should have been lowered to even greater depth when the sea floor sank.

Landes implied that the flat-topped seamounts, or guyots, were bevelled at the time the canyons were cut during the Pleistocene lowering of sea level. If sea level were lowered by sinking of the ocean floor, however, the guyots could not possibly be of the same age as the canyons for they should have been carried down with the sea floor and remained submerged. To the possible objection that they were on a stable portion of the sea floor, the rebuttal can be given that more than 100 guyots are known, mostly from the west-central and north Pacific (Hess, 1946; Menard and Dietz, 1951), but also at least one from the Atlantic (Tolstoy, 1951) and one from the Indian Ocean (Anton Bruun, Danish GALATHEA Expedition, personal communication). Referring to the photographs of ripple marks atop Sylvania Guyot near Bikini Atoll, Landes states, "I likewise believe that the deep sea-floor current ripples, like the truncated seamounts, are relics of shallower water." This belief is difficult to accept, in view of the fact that the ripples are sharp and well formed (Menard, 1952), though the guyots were probably cut during Cretaceous time (Hamilton, 1952), are related to volcanic rocks that have been exposed long enough to have become coated with manganese oxide, and are in modern deep-sea Globigerina ooze (containing no shallow-water benthonic forms, showing no solution effects, and not covered by manganese oxide). For the present it seems best to admit that we don't know how the ripples were formed.

Even more serious difficulties arise from Landes' attempt to ascribe deep-sea sands to shallow-water deposition. Ericson, Ewing, and Heezen (1951; 1952) described 12 cores near the outer Hudson Canyon from depths between 14,340 and 16,200 feet that contain sand layers ranging in thickness from films to 20 feet. That these are not former shallow-water deposits is indicated by their discontinuity, their contemporaneity with normal deep-sea sediments, their abrupt vertical transition from

and back into deep-sea sediment, and their number in individual cores. Similar layers off southern California occur in closed basins (Shepard, 1951; Emery and Rittenberg, 1952) which would have been deep lake basins if the level of the open sea were greatly lowered. Only if the water in these basins evaporated could the sands have been deposited in shallow water, but no traces of evaporites or of very widespread breaks in deposition remain. Sands and gravels have also been found near the surface of the sediment in one of the greatest deeps of the world (34,000 feet), off the Philippean Islands (Bruun, personal communication). Deposition of these sands in shallow water would require either a complete loss of oceanic water or formation of the deeps in very recent, virtually historical, time. Present-day deposition in deep water probably by turbidity currents is strongly suggested by associated terrestrial vegetation such as leaves and parts of coconut husks. Similarly, Ericson, Ewing, and Heezen (1952) have found calcareous shallow-water sediment at the bottom of the greatest deep (26,100 feet) of the Atlantic Ocean, off Puerto Rico.

One of Landes' objections to turbidity currents is that none have been observed; however, the average spacing between sandy layers found in cores is such that several hundred years would have elapsed between the deposition of the layers, and the chances of observing such a current under natural conditions during the few years of bottom photography must be negligible.

If Landes is to cling to his belief that graded sand beds, conglomerates, "misplaced Foraminifera", and deep-sea ripple marks are always relics of shallow water, he is faced by difficulties in ancient as well as in modern sediments. For instance, in the Ventura Basin of southern California there was deposited during Pliocene and Pleistocene time more than 18,000 feet of sediments which have been folded, tilted, and eroded as a result of Late Pleistocene orogeny, so that now the entire section is well exposed and can be examined in detail. It is doubtful that there exists, anywhere in the world, a better laboratory for critically studying the depositional environments of the later Tertiary sediments (Natland and Kuenen, 1951). A brief summary of the lithologic and ecologic aspect of these sediments follows.

The Pliocene series is more than 12,000 feet thick and contains 84 sand beds whose average thickness is 20 feet, with a maximum thickness of 100 feet for any one bed. It also contains 27 beds of conglomerate with an average thickness of 40 feet and a maximum of 400 feet for any one bed. These sand and conglomerate beds are separated by massive and laminated silts which, themselves, contain numerous and generally graded sand beds ranging in thickness from a parting to a few inches.

The marine Pleistocene is 2155 feet thick in the Ventura area, and it contains six sand beds, whose average thickness is 100 feet, and two conglomerate beds, each of which is about 20 feet thick. In general, the Pleistocene sequence is silty at the base and grades upward into a more sandy section. It is capped by 3600 feet of silts, sands, and conglomerates of continental origin. All of the sand and conglomerate beds are very lenticular—especially the conglomerate beds, some of which grade laterally into silt within a mile. Few, if any, beds can be traced more than 5 miles. This discontinuity clearly indicates local points of origin for the coarse beds, and therefore they, like the modern deep-sea sands, cannot be products of widespread change in sea level.

The above marine sediments are richly foraminiferal throughout, especially in the finer clastic beds, with an average of more than 1000 well-preserved specimens per cubic inch. This entire column of sediments has been sampled along several parallel traverses, at 10-foot stratigraphic intervals. The faunas in the 10,000 samples from these sections have been critically studied and the stratigraphic ranges of each species plotted graphically. Fortunately, most of the foraminiferal species in these fossil sections have living representatives on the adjacent sea floor. The bathymetric ranges of these Recent species are also known in some detail, and therefore we can determine with considerable certainty the environment of deposition of the Pliocene and Pleistocene deposits. In general, the foraminiferal distribution indicates that the lower part of the Pliocene in the Ventura area was laid down in water deeper than 4000 feet, and

that toward the top of the section a gradual shallowing took place, so that the marine sediments give way to continental deposits. There is no faunal suggestion of a gradual shallowing just below the coarse beds or of a gradual deepening just above them. As a matter of fact, most of the sand beds, and even the conglomerate beds, have thin interbeds of silt which contain the same deep-water Pliocene species found in the thick shale beds. Thus, it seems quite clear that the sand and conglomerate beds of the lower part of the Pliocene—many of which contain beautifully preserved current ripple marks—were deposited in water deeper than 4000 feet. The coarse clastics of the Upper Pliocene were deposited in water from 4000 to 900 feet deep, and the Pleistocene from 900 feet to shore.

Consequently, the above types of sediments must have been deposited without any vast oscillation of sea level, contrary to what Landes would have us believe. If his suggestion that conglomerates and sands are hallmarks of shallow environments were true, then sea level or the land elevation with respect to it rose and fell several thousand feet, at least 111 times during the Pliocene and 8 times during the Pleistocene. Moreover, it returned each time to approximately the same level after depositing a layer of sand or conglomerate during the transgression and regression phase. To accomplish this in the short time since the beginning of the Pliocene seems quite out of the question.

In addition to the 119 thick sand and conglomerate beds there are hundreds of minor sand beds, ranging in thickness from a parting to 1 foot, interbedded in laminated shale having abundant deep-water Foraminifera and scales of abyssal fish. Must sea level rise and fall hundreds of times more, some 4000 feet, to deposit a rapidly alternating series of these thinly bedded sands and shales? Like the sand beds recently found in cores from the deep oceanic basins mentioned above, these thin ancient beds are discontinuous, some lensing out within the limit of good outcrops. Would not a major oscillation of sea level leave a more profound and widespread erosional and depositional mark? How could intimately layered sands and laminated shales survive in rapidly changing levels of the sea, when in order to produce laminations we presumably must have an environment of very quiet water? Is there any other kind of evidence that during the short span since the beginning of the Pliocene Epoch the sea level rose and fell more than 1000 feet hundreds of times? The most reasonable and logical answer is that sea level did not vacillate widely, as Landes suggests, but that the coarse sediments arrived at their deep-water burial grounds via submarine slides and turbidity flows.

References Cited

Emery, K. O., and Rittenberg, S. C. (1952) *Diagenesis of California basin sediments in relation to origin of oil*, Am. Assoc. Petrol. Geol., Bull., vol. 36, p. 735–806.

Ericson, D. B., Ewing, M., and Heezen, B. C. (1951) *Deep-sea sands and submarine canyons*, Geol. Soc. Am., Bull., vol. 62, p. 961–966.

——, ——, — —— (1952) *Turbidity currents and sediments in North Atlantic*, Am. Assoc. Petrol. Geol., Bull., vol. 36, p. 489–511.

Hamilton, E. L. (1952) *Upper Cretaceous, Tertiary, and Recent planktonic Foraminifera from mid-Pacific flat-topped seamounts*, Geol. Soc. Am., Cordilleran Section, Program, p. 20–21.

Hess, H. H. (1946) *Drowned ancient islands of the Pacific basin*, Am. Jour. Sci., vol. 244, p. 772–791.

Landes, K. K. (1952) *Our shrinking globe*, Geol. Soc. Am., Bull., vol. 63, p. 225–240.

Menard, H. W. (1952) *Deep ripple marks in the sea*, Jour. Sedim. Petrol., vol. 22, p. 3–9.

—— and Dietz, R. S. (1951) *Submarine geology of the Gulf of Alaska*, Geol. Soc. Am., Bull., vol. 62, p. 1263–1286.

Natland, M. L., and Kuenen, Ph. H. (1951) *Sedimentary history of the Ventura Basin, California, and the action of turbidity currents*, Soc. Econ. Paleont. Mineral. Spec. Pub. no. 2, p. 76–107.

Shepard, F. P. (1951) *Transportation of sand into deep water*, Soc. Econ. Paleont. Mineral., Spec. Pub. no. 2, p. 53–65.

Tolstoy, I. (1951) *Submarine topography in the North Atlantic*, Geol. Soc. Am., Bull., vol. 62, p. 441–450.

University of Southern California, Los Angeles, California

Richfield Oil Corporation, Long Beach, California

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 63, PP. 1073-1074 OCTOBER 1952

OUR SHRINKING GLOBE—A REPLY

BY KENNETH K. LANDES

I am very happy that Emery and Natland have contributed the preceding Discussion, and I hope that others will do likewise. By reopening the subject for discussion I am given an opportunity for the removal of some of the inevitable ambiguities. One such has been called to my attention by letter by Professor R. W. van Bemmelen. He thought that I implied that the 8-mile subsidence during the Pleistocene was the pro-rata share for that period out of the estimated 140 miles of postulated total shrinkage of the earth's radius. Obviously on a time pro-rata basis, a figure of 8 miles for the Pleistocene would mean much more than 140 miles for preceding geologic time. What I meant to say was that contraction *at the surface* is sporadic in time and erratic in amount; the Pleistocene was a time when an unusual amount of surface shrinkage took place.

In the following reply, reference is made by paragraph number to the items discussed by Emery and Natland.

Paragraphs 2 and 3. In my paper, I advocate a lowering of sea level once during the Pleistocene of 15,000 feet *"or whatever is needed to account for subaerial canyon cutting."* I can find no area data for the sea floor between depths of 4000 meters and 5000 meters, but by interpolation of area percentages I arrive at a figure of approximately 25,000 feet as the amount of subsidence required to expose the 14,400 feet deep mouth of Hudson canyon.

Paragraph 4. If I implied that the guyots were beveled during the Pleistocene lowering of sea level, I am sorry. I cannot find such an implication, but a writer is the last one to recognize that he didn't say exactly what he meant. I visualize these marine volcanoes as being subject to wave erosion at every emergence. When subsidence of an ocean-floor segment lowered sea level, marine volcanoes everywhere except on the sinking block itself were subject to exposure and erosion, with truncation or terracing the result. At another time another segment of the sea floor sank, and the volcanoes on the block that sank previously had their opportunity for exposure above sea level. There are no stable portions of the sea floor. Through geologic time the different blocks have taken turns in grabening. Only rarely did many blocks drop concurrently; when this occurred, the lowering of sea level was abnormal, and glacial climates were a result.

Likewise I did not intend to imply that the same sea-level lowering that truncated Sylvania Guyot was responsible for the ripples on the top. At a subsequent, perhaps quite recent, sea-level lowering, the flat top of Sylvania Guyot was brought near enough to the surface so that the Globigerina ooze veneer became rippled.

Paragraph 5—*Outer Hudson Canyon deposits.* I question that discontinuity is evidence of deep-water deposition. There is nothing more discontinuous than the sand and gravel bars in a stream bed. It is my belief that the Hudson Canyon sand lenses were deposited during flood stages when this was a subaerial canyon, and that the "deep-sea" interbeds are reworked abyssal sediments obtained from the canyon walls and deposited during low-water stages.

Closed basins off Southern California. The closure is due to diastrophism. These were not always closed basins. Is there any evidence that the diastrophism took place prior to the sedimentation rather than subsequently?

Sands, gravels, leaves, and fragments of coconut hulls at 34,000 feet off the Philippine Islands. To my mind this is most interesting evidence of a very recent grabening of this great deep. The down-faulting took place at some time in the past; why could it not have occurred in "very recent, virtually historic" time?

Paragraph 6. Emery and Natland state that

on the present sea floor "several hundred years" elapse between turbidity currents so the chances of catching one in the act are almost nil. I had failed to realize the sporadic character of such currents, but had assumed that every sediment-laden stream entering the ocean at the head of a submarine canyon was a potential source of turbidity currents, especially during flood stages. According to Menard and Ludwick (p. 3) all that is needed is a sediment concentration in excess of 0.024 grams per cubic centimeter. Of course the "several hundred years" is based upon the spacing between recent *alleged* turbidity-current deposits rather than upon observations in Lakes Mead, Constance, *et al.* Turbidity currents "are always present" in Lake Mead (Gould, p. 38).

Paragraphs 7 to 12. This description of what are apparently semi-abyssal deposits in the Pliocene of the Ventura Basin is most interesting. The implied sudden dropping of the floor of the Basin to a depth of over 4000 feet is of course grist for my mill. I agree with the authors that it is illogical to assume a round-trip change in sea level of several thousand feet for each of many hundred sand and gravel layers. I am equally skeptical as to how the coarser sediment arrived on the deep sea floor "via submarine slides and turbidity flows." How could a conglomerate, over 100 feet in thickness with boulders "exceeding 2 feet in diameter" toward the bottom, slide from a place of original accumulation "off a river mouth" through a vertical distance of 4000 feet and a horizontal distance of unknown magnitude, and come to rest upon undisturbed shale so that the underlying shale, the conglomerate, and the overlying shale all contain the same deep-water fauna (Natland and Kuenen, p. 80)?

A more palatable explanation in my opinion is that the basin did sink rapidly to a maximum subsea depth greater than 4000 feet; that suspended sediment settled on the sea floor, incorporating deep-water forams in the deeper portions, and shallow-water faunas toward shore; that a lowering of the sea created shallow-water conditions over much of the basin floor, with widespread emergence of the semiabyssal muds; that rapid sedimentation followed with the cobbles deposited where currents were swift, sand where currents were more moderate, and mud where the water was quiet; and that the deep-water forams were washed out of the surrounding muds and deposited on the sea floor with the other clastic material. Later, as the basin filled with sediment, the shallow forams from the higher levels of the original sea floor were washed in and became incorporated within the younger sediments. Throughout this process where the currents were not too strong, indigenous faunas of the shallow-water type were also present and became incorporated within contemporaneous layers. Natland and Kuenen (p. 85, 86) describe the presence of Miocene fossils in the Pliocene sediments and ascribe this anomaly to redeposition from older formations. Is it not equally logical to ascribe the presence of deep water fossils in shallow water sediments to redeposition?

Conclusion. Actually, of course, whether or not there are submarine landslides and turbidity currents is beside the point that I am trying to make. The major question is, could turbidity currents have cut the submarine canyons incised in granite and other types of coherent bedrock? So far as I am aware there have been no observations made of any *abrasive* effect of such currents. Until and unless the turbiditists demonstrate abrasive ability, subaerial stream erosion continues to be the sole known adequate process. The problem is to get the ocean water out of the way. This I attempted to do in "Our Shrinking Globe".

References Cited

Three articles in *Turbidity Currents*, Soc. Econ. Geol. Paleont., Spec. Pub. no. 2, 1951, as follows:

Gould, Howard R.: *Some quantitative aspects of Lake Mead turbidity currents*, p. 34–52.

Menard, Henry W., and Ludwick, John C.: *Applications of hydraulics to the study of marine turbidity currents*, p. 2–13.

Natland, M. L., and Kuenen, Ph. H.: *Sedimentary history of the Ventura Basin, California, and the action of turbidity currents*, p. 76–107.

University of Michigan,
Ann Arbor, Mich.